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EFFECT OF MANUFACTURING PROCESSES ON STRUCTURAL ALLOWABLES—PHASE I

BATTELLE COLUMBUS DIVISION
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AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This report contains the results of tests to determine the effect of manufacturing processes on the mechanical properties of four aerospace materials, 7149-T73 hand forgings, Ti-15V-3Cr-3Sn-3Al solution treated sheet, 15-5PH (H935) castings, and Inconel 718 solution treated and aged sheet. Tensile, compression, shear, bearing, and fatigue (notched and unnotched for three stress ratios), except for 15-5PH (H935) castings, properties were obtained.

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tensile modulus of elasticity, compressive modulus of elasticity, fatigue properties. ~~7149-T73 hand forging, Ti-15V-3Cr-3Sn-3Al sheet~~, 15-~~5PH (H935) casting, and~~ ~~Inconel 718 sheet.~~

FOREWORD

This project was conducted by Battelle's Columbus Division under Contract Number F33615-84-C-5030, Project Number 2865, over the period June 29, 1984, through July 29, 1985. Mr. Neal R. Ontko (MLSE), Engineering and Design Data, Materials Engineering Branch, was the project engineer for the Materials Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. This final report covering Phase I was submitted by the author, Mr. Paul E. Ruff, in July 1985.

The author wishes to express his appreciation to Mr. Dana Jones for his effort on this project.

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SUMMARY

In order to evaluate the effect of newly established manufacturing techniques and processes on the MIL-HDBK-5 design allowable properties of aerospace materials, various mechanical properties, including fatigue, were determined at room temperature for multiple lots of four products supplied by the Air Force. The data which were obtained are suitable for the determination of statistically based design values or can be used to supplement existing data so that design values can be determined. (Statistical analysis of the data to determine design allowables was not performed in this test program.)

Specifically, the following tests were conducted in Phase I:

<u>7149-T73 Hand Forgings</u>. Tensile, compression, shear, and bearing tests in various grain directions were conducted on six lots of 7149-T73 hand forgings which varied in thickness from 2-1/2 through 4-3/4 inches in thickness. Unnotched and notched, $K_t = 3$, axial-stress fatigue tests were performed at three stress ratios, $R = -0.5$, $R = 0.1$, and $R = 0.5$, using long transverse specimens from 4-, 4-1/2-, and 4-3/4-inch-thick forgings. S/N curves were constructed.

<u>Ti-15V-3Cu-3Sn-3Al Solution Treated Sheet</u>. Tensile, compression, shear, and bearing tests in both grain directions were conducted on ten lots of solution treated Ti-15V-3Cr-3Sn-3Al sheet which varied in thickness from 0.021 through 0.116 inch. Unnotched and notched, $K_t = 3$, axial-stress fatigue tests were performed at three stress ratios, $R = -0.5$, $R = 0.1$, and $R = 0.5$, using long transverse specimens from 0.113-inch-thick sheet. S/N curves were constructed.

<u>15-5PH (H935) Castings</u>. Tensile, compression, shear, and bearing tests were conducted on nine different 15-5PH (H935) corrosion resistant steel castings which varied in thickness from 5/8 through 1-7/8 inches.

<u>Inconel 718 (STA) Sheet</u>. Tensile, compression, shear, and bearing tests in both grain directions were conducted on eight heats of solution heat treated and aged (creep-rupture heat treatment) Inconel 718 sheet which varied in thickness from 0.016 through 0.250 inch. Unnotched and notched, $K_t = 3$, axial-stress fatigue were performed at three stress ratios, $R = -0.5$, $R = 0.1$, and $R = 0.5$, using long transverse specimens from 0.109-inch-thick sheet. S/N curves were constructed.

INTRODUCTION

One of the major problems in the utilization of new manufacturing techniques for metallic materials used in advanced aircraft is the lack of sufficient comparative mechanical property data to determine the effect of a new manufacturing technique or process on the design properties of the basic material. According to DoD and FAA regulations, a material cannot be used in a structural aircraft design unless the design allowable properties are available in MIL-HDBK-5 or a statistically significant quantity of data are available to provide acceptable documentation to support the values used in the design.

Consequently, it is desirable to conduct test programs to evaluate the effects of new manufacturing techniques or processes on the basic mechanical properties, such as tension, compression, shear, and bearing properties, as well as fatigue characteristics. These data, when suitably obtained, can be used by the MIL-HDBK-5 Program to determine statistically based design values for incorporation into MIL-HDBK-5. The availability of these data will reduce the time lag between the establishment of a new manufacturing process (or alloy) and its use in aerospace vehicles and components.

OBJECTIVE

The objective of this program was to evaluate the effect of newly established manufacturing techniques and processes on the MIL-HDBK-5 design allowable properties of structural materials used in aerospace applications.

TECHNICAL APPROACH

The technical approach was to fabricate (including heat treatment when required) test specimens from government-furnished materials, to perform the mechanical property tests which are required for the development of design allowable properties, and to present the mechanical property data in a format suitable for use by the engineering community. The government-furnished materials which were tested were:

7149-T73 Hand Forgings
Ti-15V-3Cr-3Sn-3Al Sheet (Solution Treated)
Inconel 718 Sheet (Solution Treated and Aged)
15-5PH (H935) Castings.

TEST PROCEDURE

In general, triplicate specimens, except for fatigue, were conducted for each mechanical property and grain direction. However, due to the size, configuration, and quantity of material provided, some compromises were necessary. The test specimen location and configurations are described under the individual alloy in the Test Program section. All test specimens were fabricated by Metcut Research Associates, Inc., Cincinnati, Ohio. In general, all mechanical property tests were conducted in accordance with ASTM standards. A detailed description of testing procedures is provided in Appendix A. All tests were conducted at room temperature.

TEST PROGRAM

A description of the test program and the data obtained for each material are presented in this section.

7149-T73 Hand Forgings

Background

Alloy 7149 is a high strength, heat treatable aluminum alloy having good stress-corrosion resistance in the T73 temper. Alloy 7149 is similar to 7049 except for lower iron and silicon contents. Design values for 7049-T73 hand forgings are published in MIL-HDBK-5 Table 3.7.1.0(c). However, the design allowables were based upon only four lots of material. The current MIL-HDBK-5 guidelines require at least ten lots for the determination of design values. Mechanical property data for 7149-T73 hand forgings were needed for comparison with 7049-T73 data. If there are no significant differences in the tensile, compression, shear, and bearing properties for the two alloys, the 7049-T73 and 7149-T73 data can be combined so as to constitute sufficient lots of material for the determination of design values applicable to both 7049-T73 and 7149-T73 hand forgings. (After completion of this test program, comparison revealed no significant difference in the tensile, compression, shear, and bearing properties of the two alloys.)

Material

The Air Force supplied six lots of 7149-T73 hand forgings which had been produced by Kaiser Aluminum. The size of the hand forgings are shown below:

Nominal Thickness, inches	Width, inches	Length, inches
2-1/2	13-1/4	19
2-3/4	13-1/2	19
3-3/4	11-1/2	19
4	11-1/2	19
4-1/2	13-1/4	19
4-3/4	13	19

The chemical composition as determined by the AFWAL Materials Laboratory was as follows:

Element	Percent
Zinc	7.6
Magnesium	2.1
Copper	1.4
Chromium	0.14
Iron	0.108
Manganese	0.0047
Silicon	0.088
Titanium	0.016

The chemical composition and tensile properties conformed to AMS 4320.

Location of Test Specimens

In order for mechanical property data to be usable for the determination of MIL-HDBK-5 design values, the tensile, compression, shear, and bearing specimens must be located within the cross section in accordance with ASTM B557 or AMS 2355 for aluminum alloy products. All specimens, except fatigue, were taken from the middle one-third of the width with the axis of the specimen at the T/2 location but at a distance from the end of the hand forging of at least one-half the thickness of the hand forging. All tensile, compression, shear, and bearing specimens for each grain direction were located close together. Due to the limited size of the hand forgings, it was necessary to machine twenty fatigue specimens each from three hand forgings, 4, 4-1/2, and 4-3/4 inches thick. The location of the test specimens is shown in Figures 1 through 5. The following code system was used to identify test specimens:

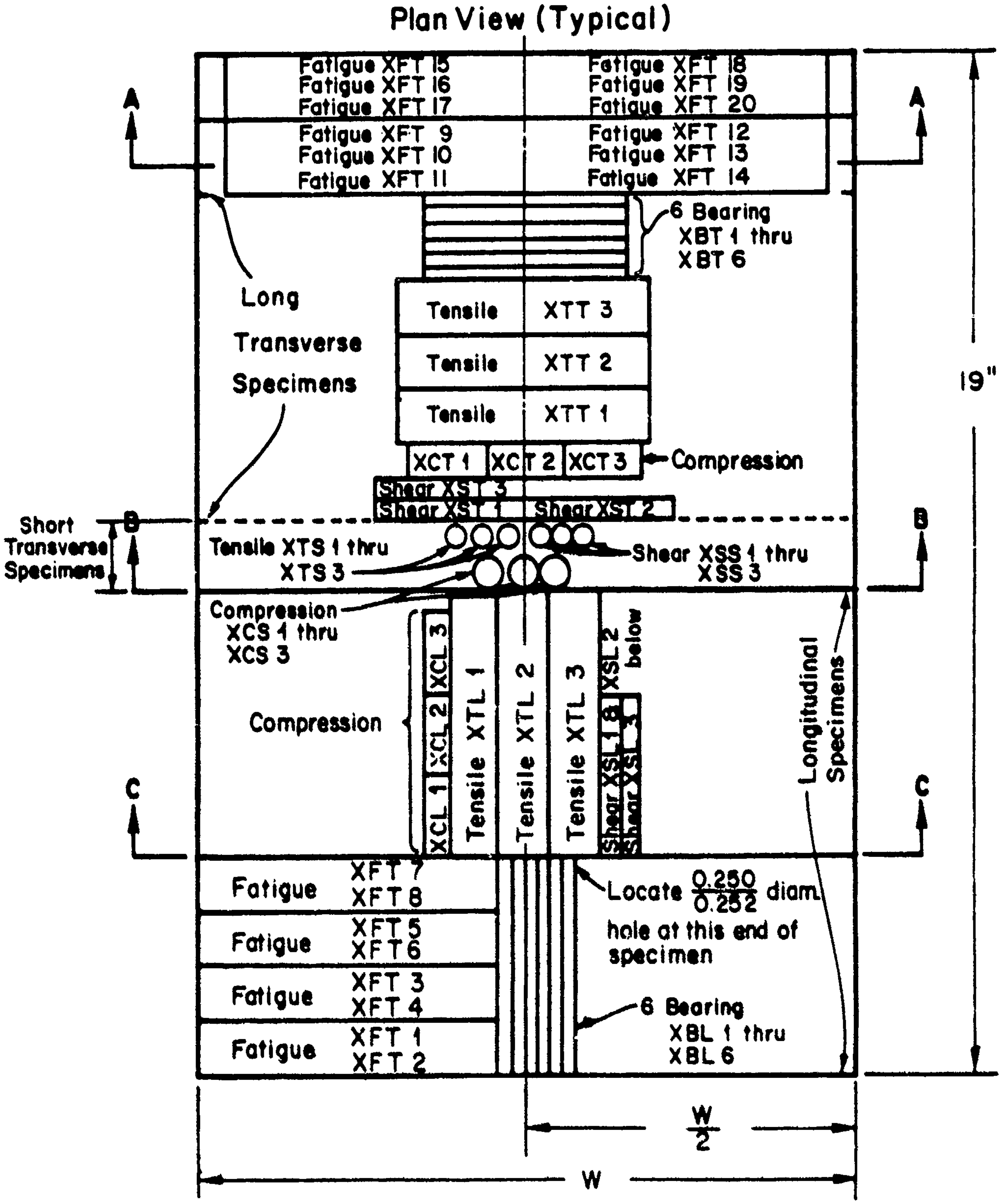


Figure 1. Specimen location for 7149-T73 hand forgings.

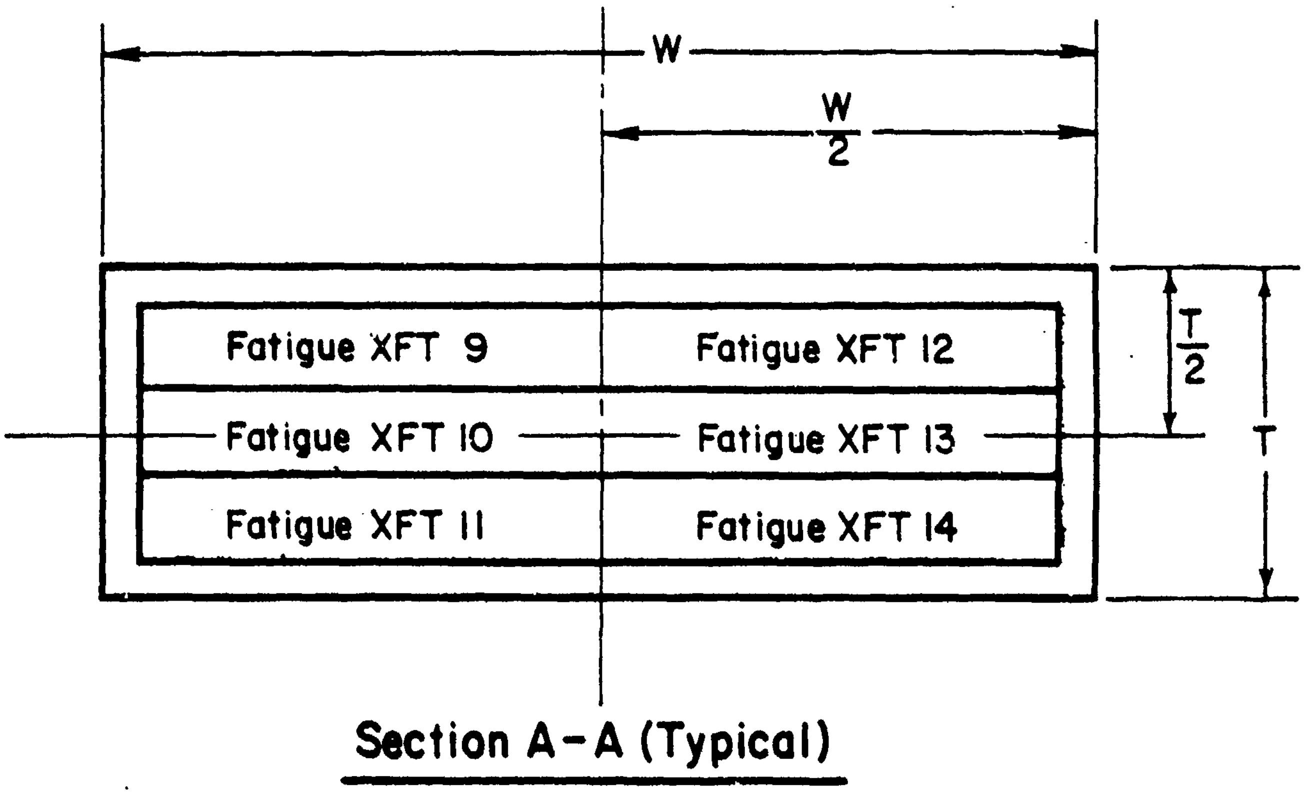


Figure 2. Specimen location for 7149-T73 hand forgings--Section A-A.

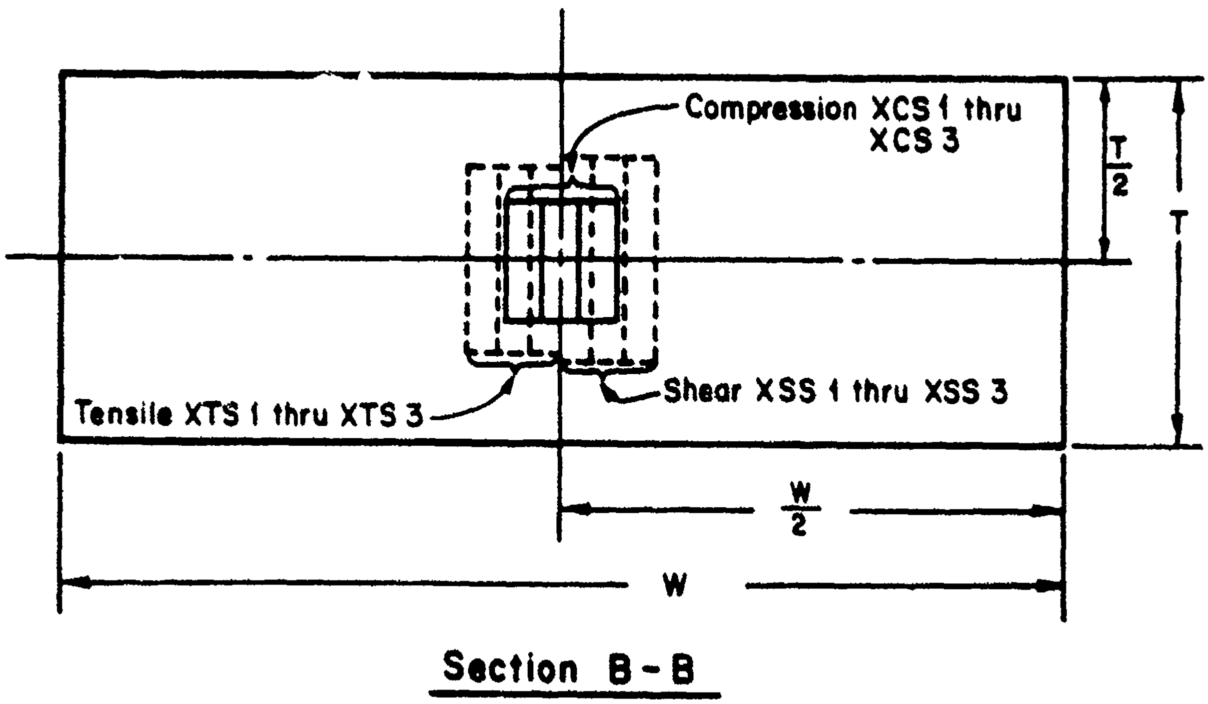
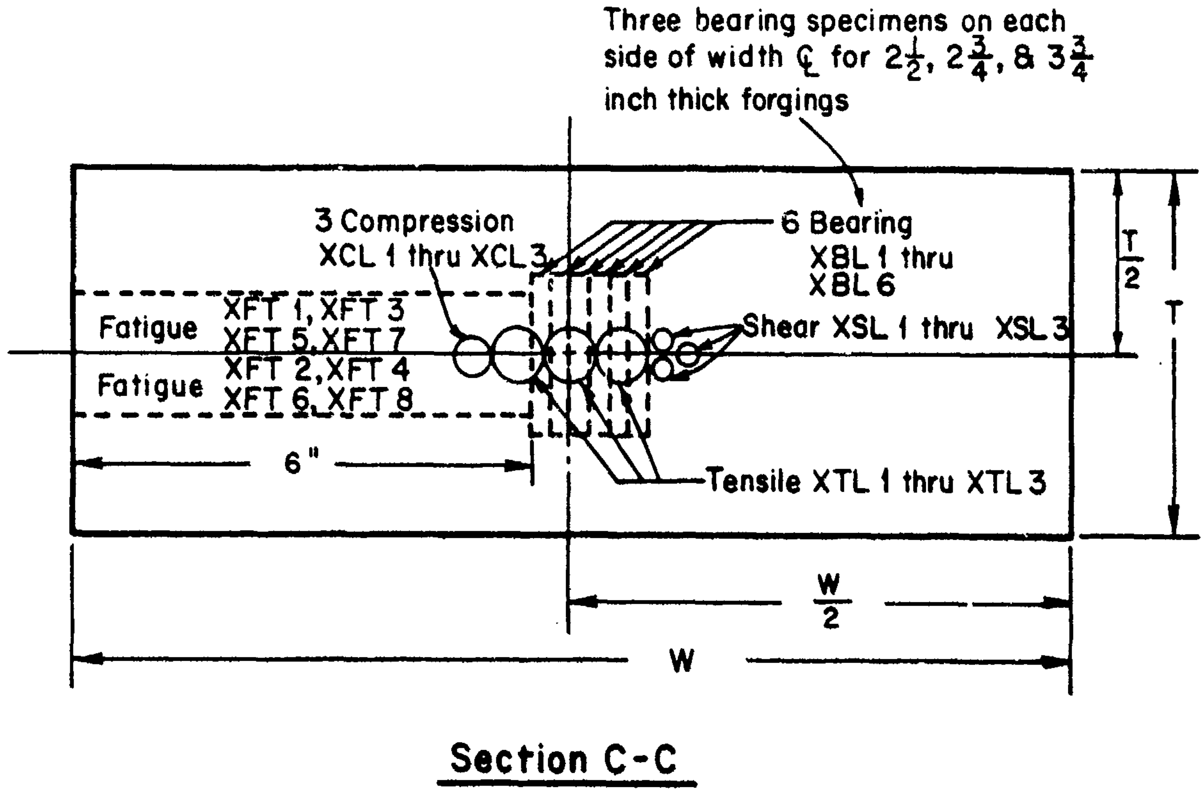


Figure 3. Specimen location for 7149-T73 hand forgings--
short transverse grain direction.



Section C-C

Figure 4. Specimen location for 7149-T73 hand forgings--longitudinal grain direction.

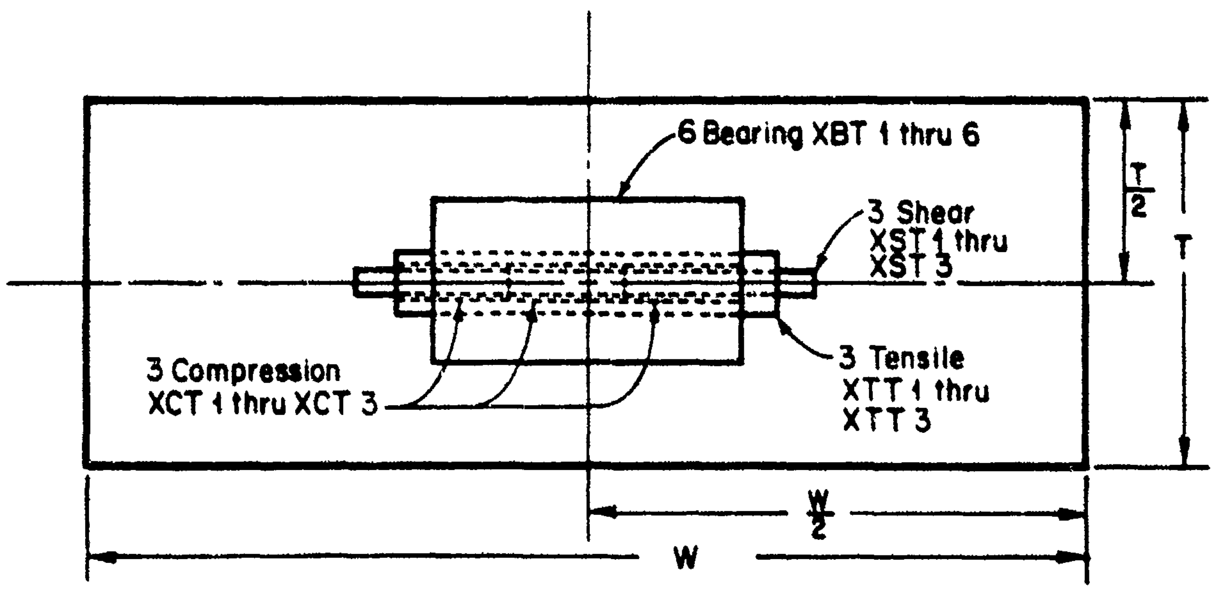


Figure 5. Specimen location for 7149-T73 hand forgings--long transverse grain direction.

X X X X

Lot Number — Type of Specimen — Grain Direction — Specimen No.

Specimen No. — 1, 2, 3, 4, etc.

Grain Direction:

Longitudinal	=	L
Long Transverse	=	T
Short Transverse	=	S

Type of Specimen:

Tension	=	T	Bearing = B
Compression	=	C	Fatigue = F
Shear	=	S	

Lot Number:

2-1/2	INCH	THICK	=	1
2-3/4	"	"	=	2
3-3/4	"	"	=	3
4	"	"	=	4
4-1/2	"	"	=	5
4-3/4	"	"	=	6

Specimen Configuration

The configurations of test specimens are shown in Appendix B. Subsize tensile specimens were employed for the short transverse grain direction.

Test Results

Tensile. The results of tensile tests are shown in Tables 1 and 1(SI). In addition to tensile yield and ultimate strengths, elongation and modulus of elasticity values are indicated. Typical tensile stress-strain curves for each grain direction are presented in Figure 6. The shape parameter was determined in accordance with Section 9.3.2 of MIL-HDBK-5D. The average tensile yield strengths and the average tensile moduli of elasticity determined in

TABLE 1. MECHANICAL PROPERTIES OF 7149-T73 HAND FORGINGS--T/2 LOCATION

Size, inches	Grain Direction	Specimen No.	Tension: Ultimate Strength, ksi	Tension: Yield Strength, ksi	Tension: Elongation, percent	Tension: Modulus, 10^3 ksi	Compressive: Yield Strength, ksi	Compressive: Modulus 10^3 ksi	Ultimate Shear[1] Strength, ksi	Bearing e/D = 1.5: Ultimate Strength, ksi	Bearing e/D = 1.5: Yield Strength, ksi	Bearing e/D = 2.0[2]: Ultimate Strength, ksi	Bearing e/D = 2.0[2]: Yield Strength ksi
2-1/2 x 13	L	1	73.0	63.5	15.0	9.1	66.2	10.3	43.6	106.0	89.0	140.6	102.0
		2	73.3	64.0	15.5	9.6	67.6	10.4	43.7	104.8	88.3	141.2	105.4
		3	73.1	64.1	14.5	9.7	66.9	10.3	42.6	105.6	89.0	140.9	103.9
		Avg.	73.1	63.9	15.0	9.5	66.9	10.3	43.3	105.5	89.0	140.9	103.9
	LT	1	72.6	64.2	14.0	10.0	67.9	10.5	42.7	114.5	92.8	148.4	106.8
		2	73.1	64.6	14.5	10.2	67.2	10.5	43.2	114.6	92.1	144.6	106.0
		3	72.9	63.7	14.0	9.5	67.5	10.6	43.2	114.5	94.8	145.5	106.6
		Avg.	72.9	64.2	14.2	9.9	67.5	10.5	43.0	114.5	93.2	146.2	106.5
	ST	1	71.7	62.8	13.0	10.2	66.2	10.0	43.3	--	--	--	--
		2	71.5	63.5	10.0[3]	10.0	66.5	10.4	43.1	--	--	--	--
		3	71.8	61.5	10.0[3]	9.9	66.7	10.5	42.9	--	--	--	--
		Avg.	71.7	62.6	13.0	10.0	66.5	10.3	43.1	--	--	--	--
2-3/4 x 13	L	1	74.1	64.7	14.5	9.6	67.2	10.2	44.2	114.5	97.2	149.8	105.4
		2	73.9	64.8	14.5	10.0	68.3	10.5	44.2	115.6	94.9	146.1	106.9
		3	73.8	64.6	14.0	10.0	68.2	10.2	42.5	113.4	91.7	145.4	106.0
		Avg.	73.9	64.7	14.3	9.9	67.9	10.3	43.6	114.5	94.6	147.1	106.1
	LT	1	74.5	66.4	14.0	10.0	69.8	10.4	41.9	109.4	91.4	144.4	106.4
		2	74.4	66.1	14.0	9.8	69.8	10.6	41.7	112.9	91.5	143.8	105.2
		3	74.1	65.2	13.5	9.6	69.2	10.6	42.7	112.1	92.6	143.6	106.6
		Avg.	74.3	65.9	13.8	9.8	69.6	10.5	42.1	111.5	91.8	143.9	106.1
	ST	1	71.5	64.3	12.0	10.5	(4)	(4)	42.7	--	--	--	--
		2	71.7	64.1	11.0	10.6	67.0	10.5	41.7	--	--	--	--
		3	71.3	62.8	8.0[3]	10.5	67.2	10.6	42.5	--	--	--	--
		Avg.	71.5	63.7	11.5	10.5	67.1	10.5	42.3	--	--	--	--

TABLE 1. MECHANICAL PROPERTIES OF 7149-T73 HAND FORGINGS--T/2 LOCATION (Continued)

Size, inches	Grain Direction	Specimen No.	Tension				Compressive		Ultimate Shear[1] Strength, ksi	Bearing			
										e/D = 1.5		e/D = 2.0[2]	
			Ultimate Strength, ksi	Yield Strength, ksi	Elongation, percent	Modulus, 10^3 ksi	Yield Strength, ksi	Modulus 10^3 ksi		Ultimate Strength, ksi	Yield Strength, ksi	Ultimate Strength, ksi	Yield Strength ksi
3-3/4 x 12	L	1	73.3	63.8	13.5	10.2	67.2	10.2	44.5	109.8	91.0	144.2	105.8
		2	73.2	64.6	13.5	9.9	68.0	10.0	43.9	108.9	90.7	147.0	107.3
		3	73.1	63.9	13.5	9.7	67.8	10.2	44.4	110.8	90.8	145.1	104.4
		Avg.	73.2	64.1	13.5	9.9	67.7	10.1	44.3	109.8	90.8	145.4	105.8
	LT	1	73.1	64.3	14.0	9.6	68.2	10.4	42.2	112.7	92.2	148.2	108.0
		2	73.4	64.1	13.5	9.7	67.9	10.4	42.4	(6)	92.0	147.8	106.0
		3	73.1	63.5	13.5	9.6	68.2	10.5	41.9	112.9	91.4	147.6	105.4
		Avg.	73.2	64.0	13.7	9.6	68.1	10.4	42.2	112.8	91.9	147.9	106.5
	ST	1	73.0	63.2	7.0[3]	10.0	67.9	10.3	44.2	--	--	--	--
		2	72.7	63.7	7.0[3]	9.2	68.2	10.5	43.9	--	--	--	--
		3	72.7	63.7	(5)	10.3	67.9	10.5	45.0	--	--	--	--
		Avg.	72.8	63.5	--	9.8	68.0	10.4	44.4	--	--	--	--
4 x 12	L	1	71.8	63.0	14.5	9.6	67.1	10.3	44.3	111.2	89.6	145.1	104.8
		2	71.9	63.1	14.5	9.6	66.0	10.1	44.1	109.4	88.8	140.4	105.2
		3	71.9	63.1	14.5	9.5	67.0	10.0	44.1	109.6	88.0	142.3	103.3
		Avg.	71.9	63.1	14.5	9.6	66.7	10.1	44.2	110.1	88.8	142.6	104.4
	LT	1	73.0	63.7	13.5	9.7	67.4	10.4	43.3	112.6	92.7	141.1	107.9
		2	73.0	63.5	13.3	9.5	67.4	10.3	43.9	113.7	70.7	138.1	107.9
		3	72.8	63.4	12.5	9.5	67.4	10.2	43.0	112.1	89.9	140.0	100.0
		Avg.	72.9	63.5	13.2	9.6	67.4	10.3	43.4	112.8	91.1	139.7	105.3
	ST	1	71.5	63.0	14.0	9.4	66.5	10.5	44.4	--	--	--	--
		2	71.9	63.3	14.0	11.8	66.6	10.5	44.2	--	--	--	--
		3	72.1	63.2	13.0	10.4	66.2	10.4	44.4	--	--	--	--
		Avg.	71.8	63.2	13.7	10.5	66.4	10.5	44.3	--	--	--	--

TABLE 1. MECHANICAL PROPERTIES OF 7149-T73 HAND FORGINGS--T/2 LOCATION (Concluded)

Size, inches	Grain Direction	Specimen No.	Tension				Compressive		Ultimate Shear Strength, ksi (1)	Bearing			
										e/D = 1.5		e/D = 2.0 (2)	
			Ultimate Strength, ksi	Yield Strength, ksi	Elongation, percent	Modulus, 10^3 ksi	Yield Strength, ksi	Modulus 10^3 ksi		Ultimate Strength, ksi	Yield Strength, ksi	Ultimate Strength, ksi	Yield Strength ksi
4-1/2 x 13	L	1	71.9	61.9	14.5	9.9	65.2	10.3	42.4	108.4	88.0	145.3	104.3
		2	71.9	62.1	13.0	10.0	65.9	10.3	43.6	112.5	89.5	142.7	102.8
		3	71.7	61.9	13.8	10.0	66.2	10.3	42.7	110.2	89.2	142.7	104.5
		Avg.	71.8	62.0	13.8	10.0	65.8	10.3	42.9	110.4	88.9	143.6	103.9
	LT	1	73.1	64.0	12.5	9.9	67.5	10.7	42.2	105.8	86.7	142.0	104.0
		2	72.9	64.2	13.8	9.8	67.2	10.5	43.2	108.9	87.1	142.2	(4)
		3	72.9	64.6	13.5	9.8	67.9	10.5	42.0	106.5	85.8	143.1	104.1
		Avg.	73.0	64.3	13.3	9.8	67.5	10.6	42.1	107.1	86.5	142.4	104.0
	ST	1	71.5	63.8	12.0	10.1	66.9	10.3	43.1	--	--	--	--
		2	72.1	63.0	12.0	10.2	67.3	10.4	43.3	--	--	--	--
		3	72.3	64.1	12.0	9.9	67.3	10.3	42.9	--	--	--	--
		Avg.	72.0	63.6	12.0	10.1	67.2	10.3	43.1	--	--	--	--
4-3/4 x 13	L	1	71.2	61.2	14.5	9.7	64.2	10.1	42.8	107.0	87.0	141.4	102.4
		2	71.3	61.3	14.0	9.9	63.9	10.1	42.3	109.7	90.1	142.9	103.7
		3	71.5	61.4	14.0	9.9	64.0	10.3	42.7	108.9	92.5	143.0	106.0
		Avg.	71.3	61.3	14.2	9.8	64.0	10.2	42.6	108.5	89.9	142.4	104.0
	LT	1	71.9	62.8	12.5	9.9	65.1	10.3	41.7	104.8	82.7	138.7	102.8
		2	71.7	62.8	13.5	10.0	65.5	10.4	41.7	107.8	86.9	141.0	103.2
		3	72.0	62.7	13.3	9.9	64.8	10.5	42.5	(6)	85.9	144.0	105.2
		Avg.	71.9	62.8	13.1	9.9	65.1	10.4	42.0	106.3	85.2	141.2	103.7
	ST	1	70.9	59.8	10.0 (3)	9.8	65.4	10.5	42.3	--	--	--	--
		2	71.3	60.2	10.0	9.8	65.6	10.6	41.9	--	--	--	--
		3	71.1	60.3	12.0	10.8	65.2	10.5	42.0	--	--	--	--
		Avg.	71.1	60.1	11.0	10.1	65.4	10.5	42.1	--	--	--	--

(1) "Amsler" double shear pin tests.
(2) Specimen numbers for e/D = 2.0 were 4 through 6.
(3) Failed at or near punchmark or outside gage length--not included in average.
(4) Chart recorder malfunctioned.
(5) Punchmark not discernible.
(6) Pin failed.

TABLE 1 (SI). MECHANICAL PROPERTIES OF 7149-T73 HAND FORGINGS - T/2 LOCATION

Size, mm	Grain Direction	Specimen No.	Tensile Ultimate Strength, MPa	Tensile Yield Strength, MPa	Tensile Elongation, percent	Tensile Modulus, GPa	Compressive Yield Strength, MPa	Compressive Modulus GPa	Ultimate Shear(1) Strength, MPa	Bearing e/D = 1.5 Ultimate Strength, MPa	Bearing e/D = 1.5 Yield Strength, MPa	Bearing e/D = 2.0(2) Ultimate Strength, MPa	Bearing e/D = 2.0(2) Yield Strength, MPa
64 x 330	L	1	503.3	437.8	15.0	62.7	456.4	71.0	300.6	730.9	613.7	969.4	703.3
		2	505.4	441.3	15.5	66.2	466.1	71.7	301.3	722.6	608.8	973.6	726.7
		3	504.0	442.0	14.5	66.9	461.3	71.0	293.7	728.1	617.8	972.2	719.8
		Avg.	504.0	440.1	15.0	65.5	461.3	71.2	298.5	726.9	613.4	917.7	716.6
	LT	1	500.6	442.7	14.0	69.0	468.2	72.4	294.4	789.5	639.9	1023.2	736.4
		2	504.0	445.4	14.5	70.3	463.3	72.4	297.9	790.2	635.0	997.0	730.9
		3	502.6	439.2	14.0	65.5	465.4	73.1	297.9	789.5	653.6	1003.2	735.0
		Avg.	502.4	442.4	14.2	68.3	465.6	72.6	296.7	789.7	642.8	1007.8	734.1
	ST	1	494.4	433.0	13.0	70.3	456.4	69.0	298.6	-	-	-	-
		2	493.0	437.8	10.0(3)	69.0	458.5	71.7	297.2	-	-	-	-
		3	495.1	424.0	10.0(3)	68.3	459.9	72.4	295.8	-	-	-	-
		Avg.	494.2	431.6	13.0	69.2	458.3	71.0	297.2	-	-	-	-
70 x 330	L	1	510.9	446.1	14.5	66.2	463.3	70.3	304.8	789.5	670.2	1032.9	726.7
		2	509.5	446.8	14.5	69.0	470.9	72.4	304.8	797.1	654.3	1007.4	737.1
		3	508.9	445.4	14.0	69.0	470.2	70.3	293.0	781.9	632.3	1002.5	730.9
		Avg.	509.8	446.1	14.3	68.1	468.1	71.0	300.9	789.5	652.3	1014.2	731.6
	LT	1	513.7	457.8	14.0	69.0	481.3	71.7	288.9	754.3	630.2	995.6	733.6
		2	513.0	455.8	14.0	67.6	481.3	73.1	287.5	778.4	630.9	991.5	725.4
		3	510.9	449.6	13.5	66.2	477.1	73.1	294.4	772.9	638.5	990.1	735.0
		Avg.	512.5	454.4	13.8	67.6	480.0	72.6	290.3	767.9	633.2	992.4	731.3
	ST	1	493.0	443.3	12.0	72.4	(4)	(4)	294.4	-	-	-	-
		2	494.4	442.0	11.0	73.1	462.0	72.4	287.5	-	-	-	-
		3	491.6	433.0	8.0(3)	72.4	463.3	73.1	293.0	-	-	-	-
		Avg.	493.0	439.3	11.5	72.6	462.6	72.7	291.6	-	-	-	-

TABLE 1 (SI). MECHANICAL PROPERTIES OF 7149-T73 HAND FORGINGS - T/2 LOCATION (Continued)

Size, mm	Grain Direction	Specimen No.	Tensile				Compressive		Ultimate Shear(1) Strength, MPa	Bearing			
										e/D = 1.5		e/D = 2.0(2)	
			Ultimate Strength, MPa	Yield Strength, MPa	Elongation, percent	Modulus, GPa	Yield Strength, MPa	Modulus GPa		Ultimate Strength, MPa	Yield Strength, MPa	Ultimate Strength, MPa	Yield Strength, MPa
95 x 305	L	1	505.4	439.9	13.5	70.3	463.3	70.3	306.8	757.1	627.4	994.3	729.5
		2	504.7	445.4	13.5	68.3	468.9	69.0	302.7	750.9	625.4	1013.6	739.8
		3	504.0	440.6	13.5	66.9	467.5	70.3	306.1	764.0	626.1	1000.5	719.8
		Avg.	504.7	442.0	13.5	68.5	466.6	69.9	305.2	757.3	626.3	1002.8	729.7
	LT	1	504.4	443.3	14.0	66.2	470.2	71.7	291.0	777.1	635.7	1021.8	744.7
		2	506.1	442.0	13.5	66.9	468.2	71.7	292.3	(6)	634.3	1019.1	730.9
		3	504.4	437.8	13.5	66.2	470.2	72.4	288.9	778.4	630.2	1017.7	726.7
		Avg.	505.0	441.0	13.7	66.4	469.5	71.9	290.7	777.8	633.4	1019.3	734.1
	ST	1	503.3	435.8	7.0(3)	69.0	468.2	71.0	304.8	-	-	-	-
		2	501.3	439.2	7.0(3)	63.4	470.2	72.4	302.7	-	-	-	-
		3	501.3	439.2	(5)	71.0	468.2	72.4	310.3	-	-	-	-
		Avg.	502.0	438.1	--	67.8	468.9	71.9	305.9	-	-	-	-
101 x 305	L	1	495.1	434.4	14.5	66.2	462.7	71.0	305.4	766.7	617.8	1000.5	722.6
		2	495.8	435.1	14.5	66.2	455.1	69.9	304.1	754.3	612.3	968.1	725.4
		3	495.8	435.1	14.5	65.5	462.0	69.0	304.1	755.7	606.8	981.2	712.3
		Avg.	495.6	434.9	14.5	66.0	459.9	70.0	304.5	758.9	612.3	983.3	720.1
	LT	1	503.3	439.2	13.5	66.9	464.7	71.7	298.6	776.4	639.2	972.9	744.0
		2	503.3	437.8	13.3	65.5	464.7	71.0	302.7	784.0	625.4	952.2	744.0
		3	502.0	437.1	12.5	65.5	464.7	70.3	296.5	772.9	619.9	965.3	689.5
		Avg.	502.9	438.0	13.2	66.0	464.7	71.0	299.3	777.8	628.2	963.5	725.8
	ST	1	493.0	434.4	14.0	64.8	458.5	72.4	306.1	-	-	-	-
		2	495.8	436.5	14.0	81.4	459.2	72.4	304.8	-	-	-	-
		3	497.1	435.8	13.0	72.7	456.4	71.7	306.1	-	-	-	-
		Avg.	495.3	435.6	13.7	72.6	458.0	72.2	305.7	-	-	-	-

TABLE 1 (SI). MECHANICAL PROPERTIES OF 7149-T73 HAND FORGINGS - T/2 LOCATION (Concluded)

Size, mm	Grain Direction	Specimen No.	Tensile Ultimate Strength, MPa	Tensile Yield Strength, MPa	Tensile Elongation, percent	Tensile Modulus, GPa	Compressive Yield Strength, MPa	Compressive Modulus GPa	Ultimate Shear(1) Strength MPa	Bearing e/D = 1.5 Ultimate Strength, MPa	Bearing e/D = 1.5 Yield Strength, MPa	Bearing e/D = 2.0(2) Ultimate Strength, MPa	Bearing e/D = 2.0(2) Yield Strength MPa
114 x 330	L	1	495.8	426.8	14.5	68.3	449.6	71.0	292.3	747.4	606.8	1001.8	719.1
		2	495.8	428.2	13.0	69.0	454.4	71.0	300.6	775.7	617.1	983.9	708.8
		3	494.4	426.8	13.8	69.0	456.4	71.0	294.4	759.8	615.0	983.9	720.5
		Avg	495.3	427.3	13.8	68.8	453.5	71.0	295.8	761.0	613.0	989.9	716.1
	LT	1	504.0	441.3	12.5	68.3	465.4	73.8	291.0	729.5	597.8	979.1	717.1
		2	502.6	442.7	13.8	67.6	463.3	72.4	291.0	750.9	600.6	980.5	(4)
		3	502.6	445.4	13.5	67.6	468.2	72.4	289.6	734.3	591.6	986.7	717.8
		Avg.	503.1	443.1	13.3	67.8	456.6	72.9	290.5	738.2	596.7	982.1	717.4
	ST	1	493.0	439.9	12.0	69.6	461.3	71.0	297.2	-	-	-	-
		2	497.1	434.4	12.0	70.3	464.0	71.7	298.6	-	-	-	-
		3	498.5	442.0	12.0	68.3	464.0	71.0	295.8	-	-	-	-
		Avg.	496.2	438.8	12.0	69.4	463.1	71.2	297.2	-	-	-	-
120 x 330	L	1	490.9	422.0	14.5	66.9	442.7	69.6	295.1	737.8	599.9	975.0	706.0
		2	491.6	422.7	14.0	68.3	440.6	69.6	291.7	756.4	621.2	985.3	715.0
		3	493.0	423.4	14.0	68.3	441.3	71.0	294.4	750.9	637.8	986.0	730.9
		Avg.	491.5	422.7	14.2	67.8	441.5	70.1	293.7	748.4	619.6	982.1	717.3
	LT	1	495.8	433.0	12.5	68.3	448.9	71.0	287.5	722.6	570.2	956.3	708.8
		2	494.4	433.0	13.5	69.0	451.6	71.7	287.5	743.3	599.2	972.2	711.6
		3	496.4	432.3	13.3	68.3	446.8	72.4	293.0	(6)	592.3	982.9	725.4
		Avg.	495.5	432.8	13.1	68.5	449.1	71.7	289.3	733.0	587.2	973.8	715.3
	ST	1	488.9	412.3	10.0(3)	67.6	450.9	72.4	291.9	-	-	-	-
		2	491.6	415.1	10.0	67.6	452.3	73.1	288.8	-	-	-	-
		3	490.2	415.8	12.0	74.5	449.6	72.4	289.5	-	-	-	-
		Avg.	490.2	414.4	11.0	69.6	450.9	72.6	290.1	-	-	-	-

(1) "Amsler" double shear pin tests.
(2) Specimen numbers for e/D = 2.0 were 4 through 6.
(3) Failed at or near punch mark or outside gage length--not included in average.
(4) Chart recorder malfunctioned.
(5) Punchmark not discernable.
(6) Pin failed.

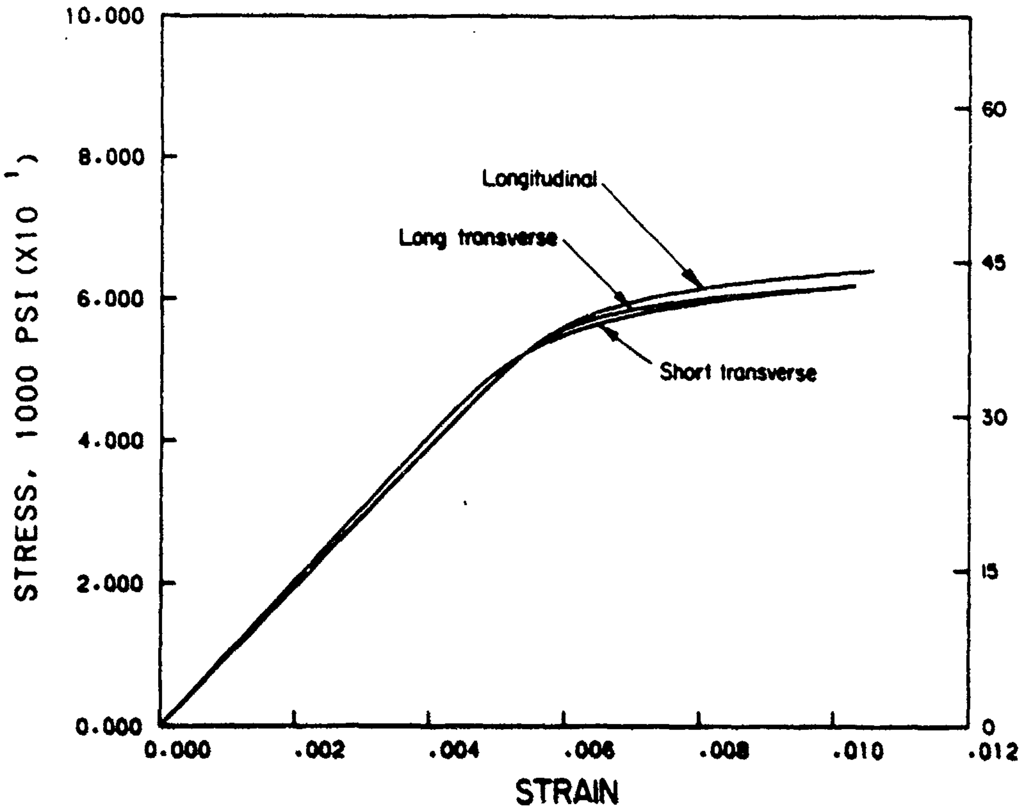


Figure 6. Typical tensile stress-strain curves for 7149-T73 hand forgings.

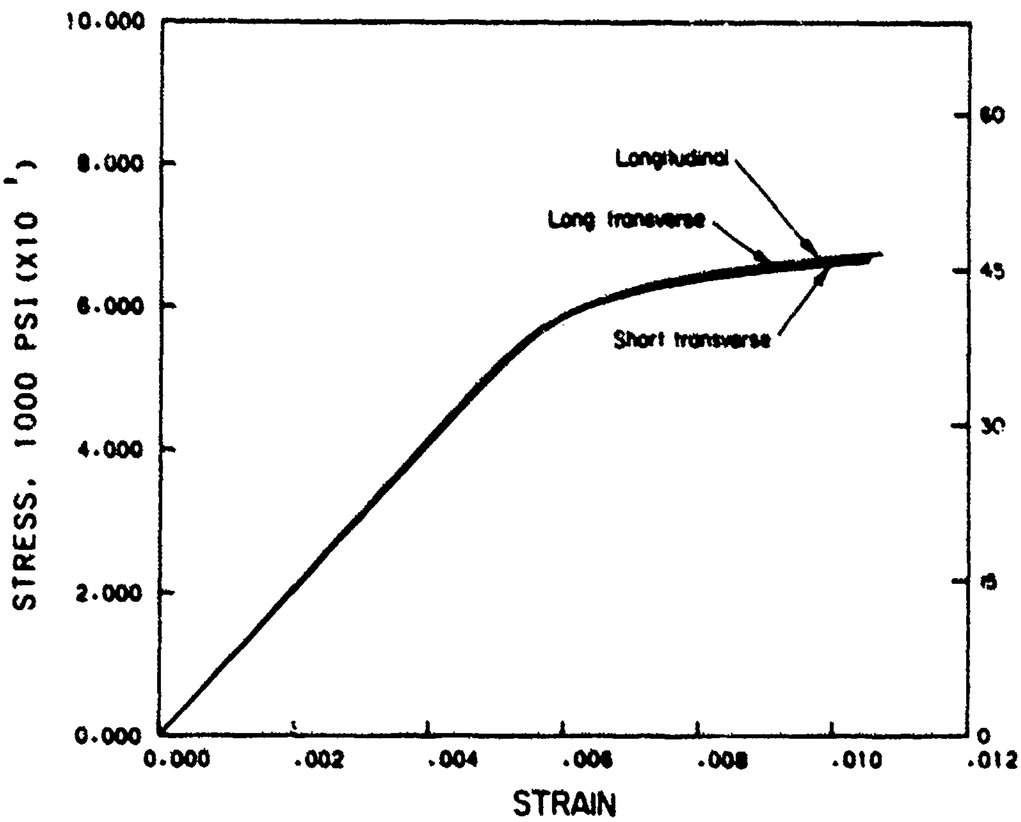


Figure 7. Typical compressive stress-strain curves for 7149-T73 hand forgings.

this test program were used with the shape parameter to construct typical stress-strain curves.

Compression. The results of compression tests are shown in Tables 1 and 1(SI). Compressive modulus of elasticity values are listed in addition to the compressive yield strengths. Typical compressive stress-strain curves are presented in Figure 7 for each grain direction. The shape parameter was determined in accordance with Section 9.3.2 of MIL-HDBK-5D. The average compressive yield strengths and average compressive moduli of elasticity determined in this test program were used with the shape parameter to construct typical stress-strain curves.

Shear. The results of shear tests are shown in Tables 1 and 1(SI). An "Amsler" shear specimen and "Amsler" shear tool were used for testing so that the resulting shear data would be compatible with existing shear data for 7049-T73 hand forgings as well as other aluminum alloy products. The shear strength of aluminum alloys may vary with grain direction. Therefore, the identity of the grain orientation of the shear specimens was maintained with a scribe mark on the end of the specimen and the shear specimens were positioned in the "Amsler" shear fixture so that the loading direction was in accordance with MIL-HDBK-5 Section 3.1.2.1.1.

Bearing. The results of bearing tests are shown in Table 1. Bearing specimens were located in an edgewise orientation. Bearing tests were not conducted in the short transverse direction.

Fatigue. The results of axial-stress fatigue tests are shown in Tables 2 and 3. Fatigue tests were conducted only in the long transverse grain direction utilizing unnotched and notched, $K_t = 3$, specimens. The thicknesses of the hand forgings tested were 4, 4-1/2, and 4-3/4 inches. Tests were conducted at three stress ratios, $R = -0.5$, $R = 0.1$, and $R = 0.5$. The fatigue data were analyzed in accordance with Section 9.3.4 of MIL-HDBK-5 and S/N curves in Figures 8 and 9 constructed accordingly.

TABLE 2. UNNOTCHED FATIGUE DATA FOR 7149-T73 HAND FORGINGS--LONG TRANSVERSE DIRECTION

Specimen ID	Maximum Stress ksi (MPa)	R-ratio	Cycles to Failure	
6FT5	62.0 (427.5)	-0.5	8,080	
5FT13	60.0 (413.7)	-0.5	12,290	
6FT11	60.0 (413.7)	-0.5	21,690	
5FT9	50.0 (344.8)	-0.5	41,600	
4FT9	50.0 (344.8)	-0.5	49,600	
6FT13	45.0 (310.3)	-0.5	46,850	
4FT11	40.0 (275.8)	-0.5	-	(1)
6FT9	40.0 (275.8)	-0.5	513,530	
5FT7	35.0 (241.3)	-0.5	DNF	(2)
4FT13	30.0 (206.9)	-0.5	DNF	
4FT15	60.0 (413.7)	+0.1	23,720	
5FT15	60.0 (413.7)	+0.1	32,360	
6FT7	55.0 (379.2)	+0.1	54,070	
5FT19	55.0 (379.2)	+0.1	137,730	
6FT15	50.0 (344.8)	+0.1	81,300	
4FT17	50.0 (344.8)	+0.1	96,720	
6FT17	45.0 (310.3)	+0.1	DNF	
6FT19	45.0 (310.3)	+0.1	DNF	
5FT17	40.0 (275.8)	+0.1	2,000,000	
4FT19	40.0 (275.8)	+0.1	DNF	
5FT11	35.0 (241.3)	+0.1	DNF	
4FT7	62.0 (427.5)	+0.5	34,370	
4FT1	60.0 (413.7)	+0.5	88,410	
6FT3	60.0 (413.7)	+0.5	7,503,000	
5FT1	60.0 (413.7)	+0.5	9,265,650	
5FT3	55.0 (379.2)	+0.5	33,280	
6FT1	55.0 (379.2)	+0.5	96,390	
4FT5	50.0 (344.8)	+0.5	-	(3)
4FT3	50.0 (344.8)	+0.5	DNF	
5FT5	50.0 (344.8)	+0.5	DNF	

(1) Counter did not stop; unknown cycles to failure.

(2) DNF--did not fail; test ran to 10,000,000 cycles and stopped.

(3) Unknown load for 10,000+ cycles.

TABLE 3. NOTCHED, K_t = 3, FATIGUE DATA FOR 7149-T73 HAND FORGINGS--LONG TRANSVERSE DIRECTION

Specimen ID	Maximum Stress ksi (MPa)	R-ratio	Cycles to Failure
5FT10	30.0 (206.9)	-0.5	7,050
4FT10	30.0 (206.9)	-0.5	7,090
6FT10	20.0 (137.9)	-0.5	52,260
4FT12	20.0 (137.9)	-0.5	81,290
5FT14	17.5 (120.7)	-0.5	77,840
6FT12	17.5 (120.7)	-0.5	82,670
5FT8	15.0 (103.4)	-0.5	233,960
6FT14	15.0 (103.4)	-0.5	1,341,750
4FT14	15.0 (103.4)	-0.5	DNF (1)
5FT12	10.0 (68.9)	-0.5	DNF
5FT20	40.0 (275.8)	+0.1	5,190
6FT8	40.0 (275.8)	+0.1	6,400
6FT16	30.0 (206.9)	+0.1	20,050
4FT16	30.0 (206.9)	+0.1	22,480
5FT18	25.0 (172.4)	+0.1	36,370
6FT18	25.0 (172.4)	+0.1	47,780
4FT18	20.0 (137.9)	+0.1	636,160
5FT16	20.0 (137.9)	+0.1	9,282,210
4FT20	15.0 (103.4)	+0.1	DNF
6FT20	15.0 (103.4)	+0.1	DNF
5FT6	55.0 (379.2)	+0.5	7,740
5FT2	50.0 (344.8)	+0.5	10,440
6FT6	50.0 (344.8)	+0.5	11,600
5FT4	40.0 (275.8)	+0.5	28,880
4FT8	40.0 (275.8)	+0.5	31,200
4FT6	30.0 (206.9)	+0.5	125,590
4FT2	25.0 (172.4)	+0.5	56,780
6FT4	25.0 (172.4)	+0.5	286,150
6FT2	20.0 (137.9)	+0.5	233,150
4FT4	20.0 (137.9)	+0.5	DNF

(1) DNF--did not fail; test ran to 10,000,000 cycles and stopped.

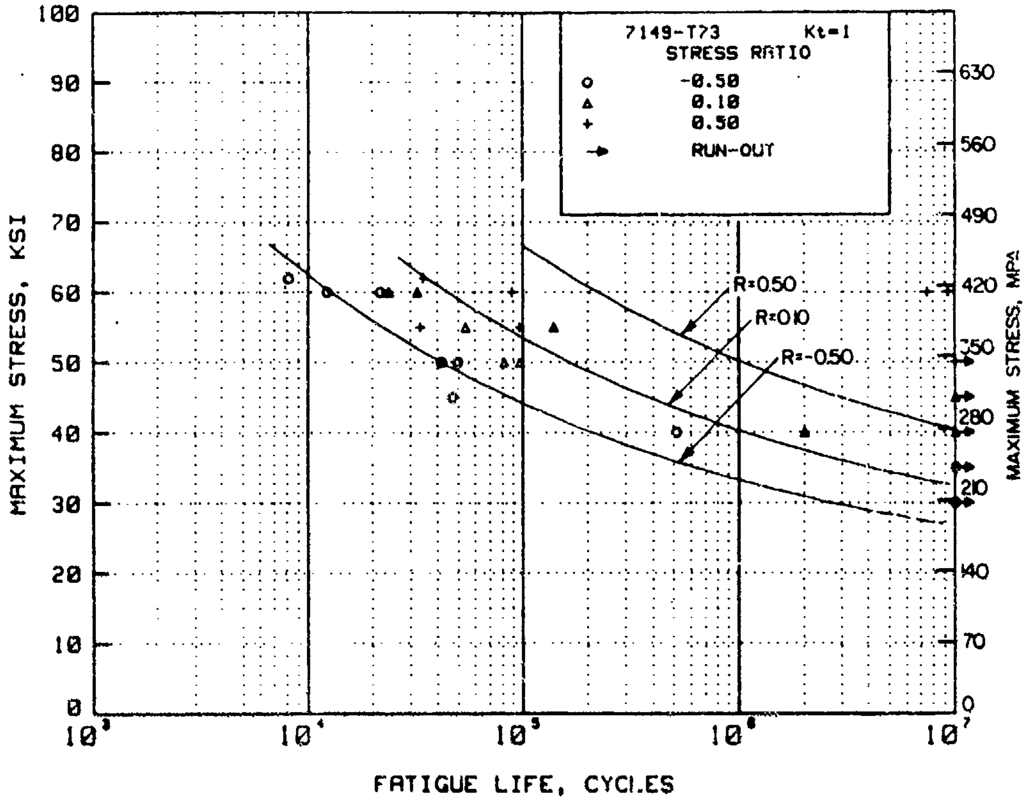


Figure 8. Unnotched axial-stress S/N curves for 7149-T73 hand forgings--long transverse grain direction, 4, 4-1/2, and 4-3/4 inches thick.

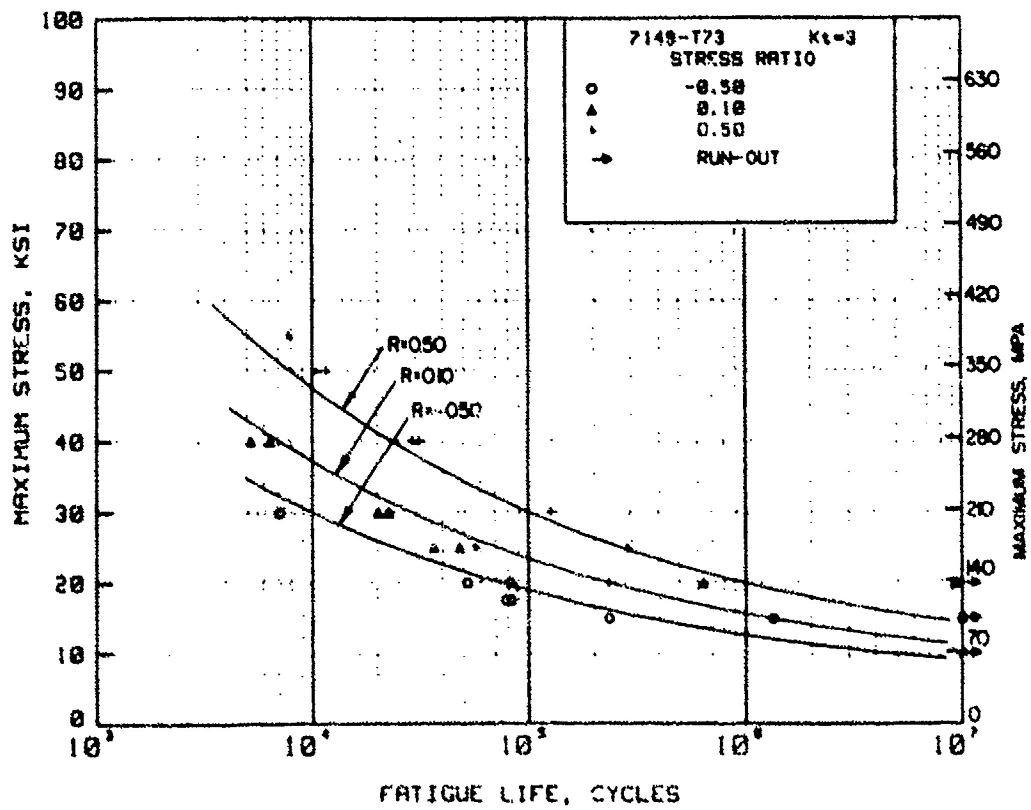


Figure 9. Notched axial-stress S/N curves for 7149-T73 hand forgings--long transverse grain direction, 4-, 4-1/2, and 4-3/4 inches thick.

Ti-15V-3Cr-3Sn-3Al Sheet (Solution Heat Treated)

Background

Alloy Ti-15V-3Cr-3Sn-3Al is a near-beta titanium sheet alloy which can be economically cold formed. The alloy is normally used in the solution treated and aged condition. Several aerospace companies are using this product as a replacement for aluminum sheet-metal structures because of economic considerations. For the replacement of aluminum structure, the high strength properties of solution treated and aged material are not required. Therefore, the Ti-15V-3Cr-3Sn-3Al sheet is used in the as-supplied, solution heat treated condition to avoid the cost of heat treatment. Consequently, it was desirable to determine the mechanical properties of Ti-15V-3Cr-3Sn-3Al sheet in the solution treated condition so that design values can be subsequently determined. (TIMET has provided mechanical property data for the determination of minimum design values for the solution treated and aged condition.)

Material

The Air Force supplied ten lots of Ti-15V-3Cr-3Al-3Sn sheet which had been produced by TIMET. The ten lots represented five heats for which the chemical composition, as determined by TIMET, is shown below:

	Percent				
Element	P6560	P6562	S6928	S8373	S9343
Vanadium	15.1	15.0	15.3	15.3	15.0
Aluminum	2.95	2.97	3.00	3.00	3.05
Chromium	3.05	3.00	2.97	2.97	3.14
Tin	2.90	3.00	2.98	2.98	2.58
Carbon	0.020	0.018	0.017	0.021	0.013
Iron	0.145	0.016	0.016	0.016	0.140
Nitrogen	0.013	0.010	0.021	0.021	0.013
Hydrogen	--	--	0.012	0.006	0.007
Oxygen	0.130	0.113	--	--	--

The chemical compositions and tensile properties conformed to AMS 4914.

The size of the sheet received for testing and the heat number are shown below:

Nominal Thickness, inches	Width, inches	(Long. Grain Dir.) Length, inches	Heat Number
0.021	34	21	P6562
0.023	24	15	S8373
0.040	12	24	S6928
0.051	19	22	P6560
0.052	17	20	P6562
0.056	15	24	S8373
0.063	13	24	S9343
0.072	19	31	S8373
0.113	24	24	P6562
0.116	17	20	P6562

Location of Test Specimens

The location of test specimens is shown in Figures 10 through 12. The following code system was used to identify test specimens:

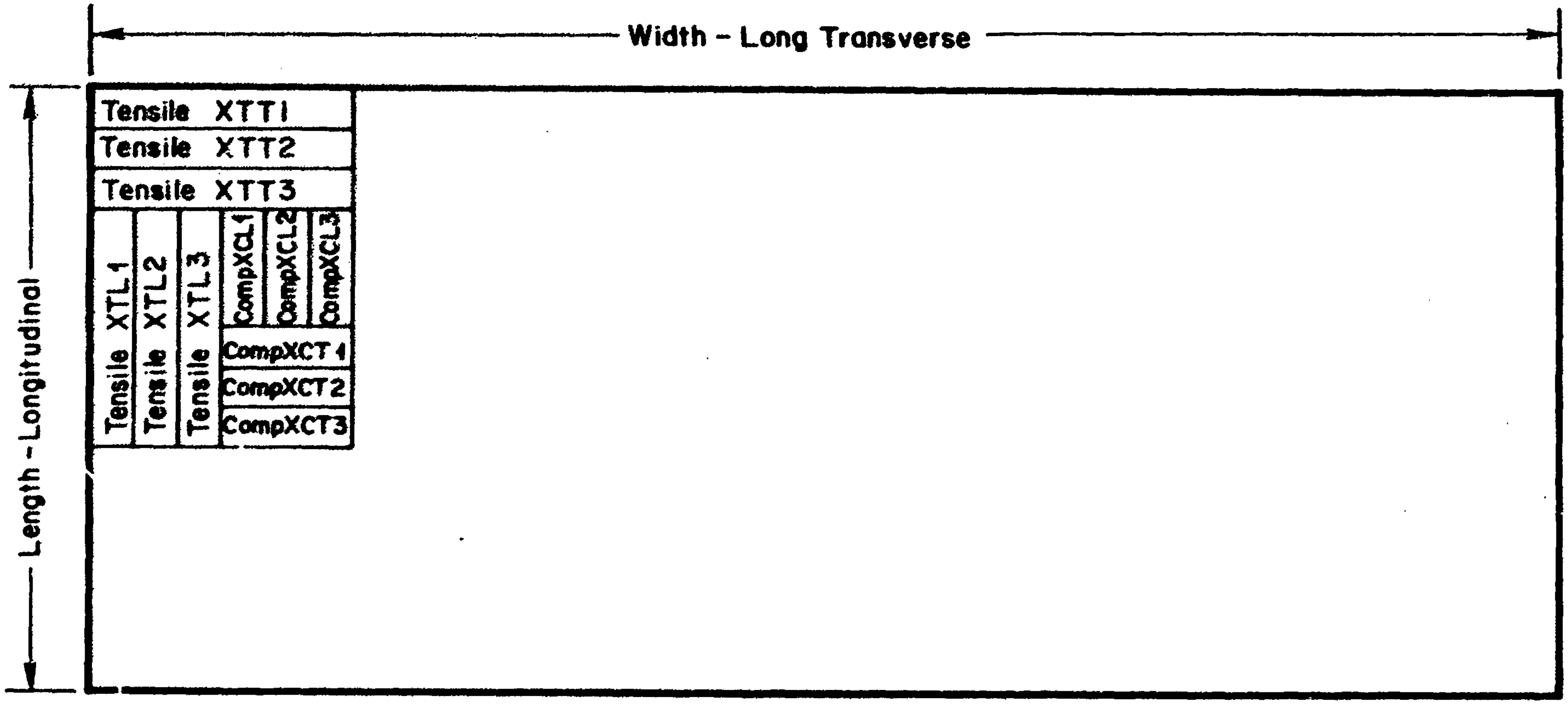


Figure 10. Location of test specimens for Ti-15V-3Cr-3Sn-3Al sheet--0.021 (P6562), and 0.023 (S8373) inches thick.

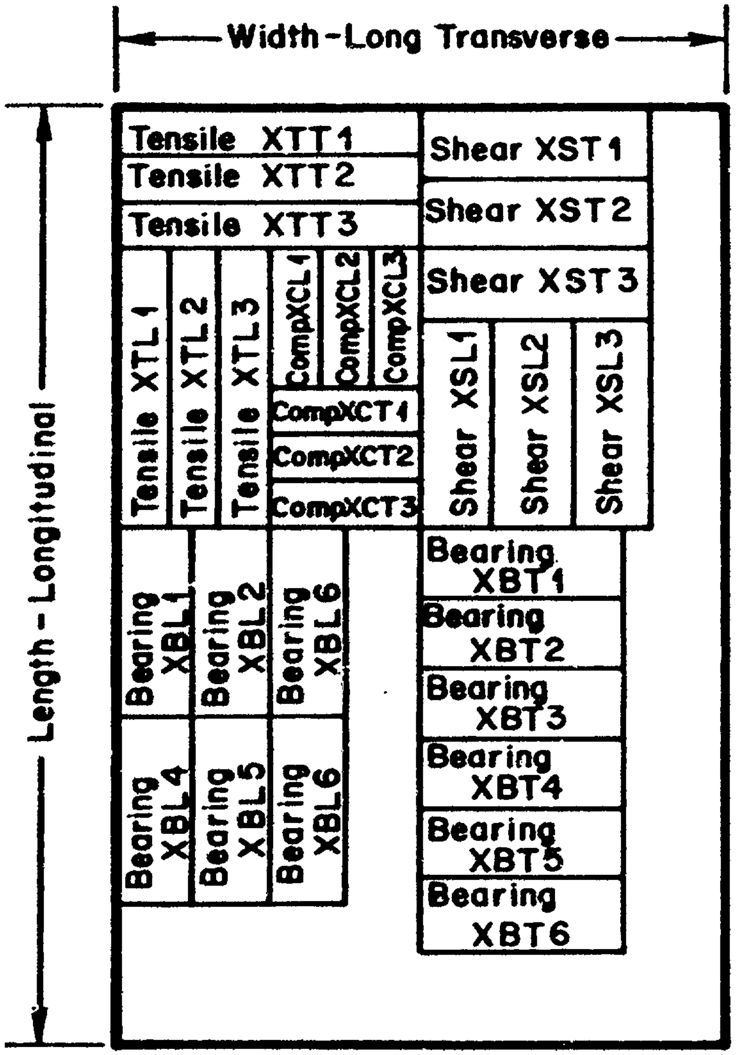


Figure 11. Typical location of test specimens for Ti-15V-3Cr-3Sn-3Al sheet--0.040 (S6928), 0.051 (P6560), 0.052 (P6562), 0.056 (S8373), 0.063 (S9343), 0.072 (S8373), and 0.116 (P6562) inches thick.

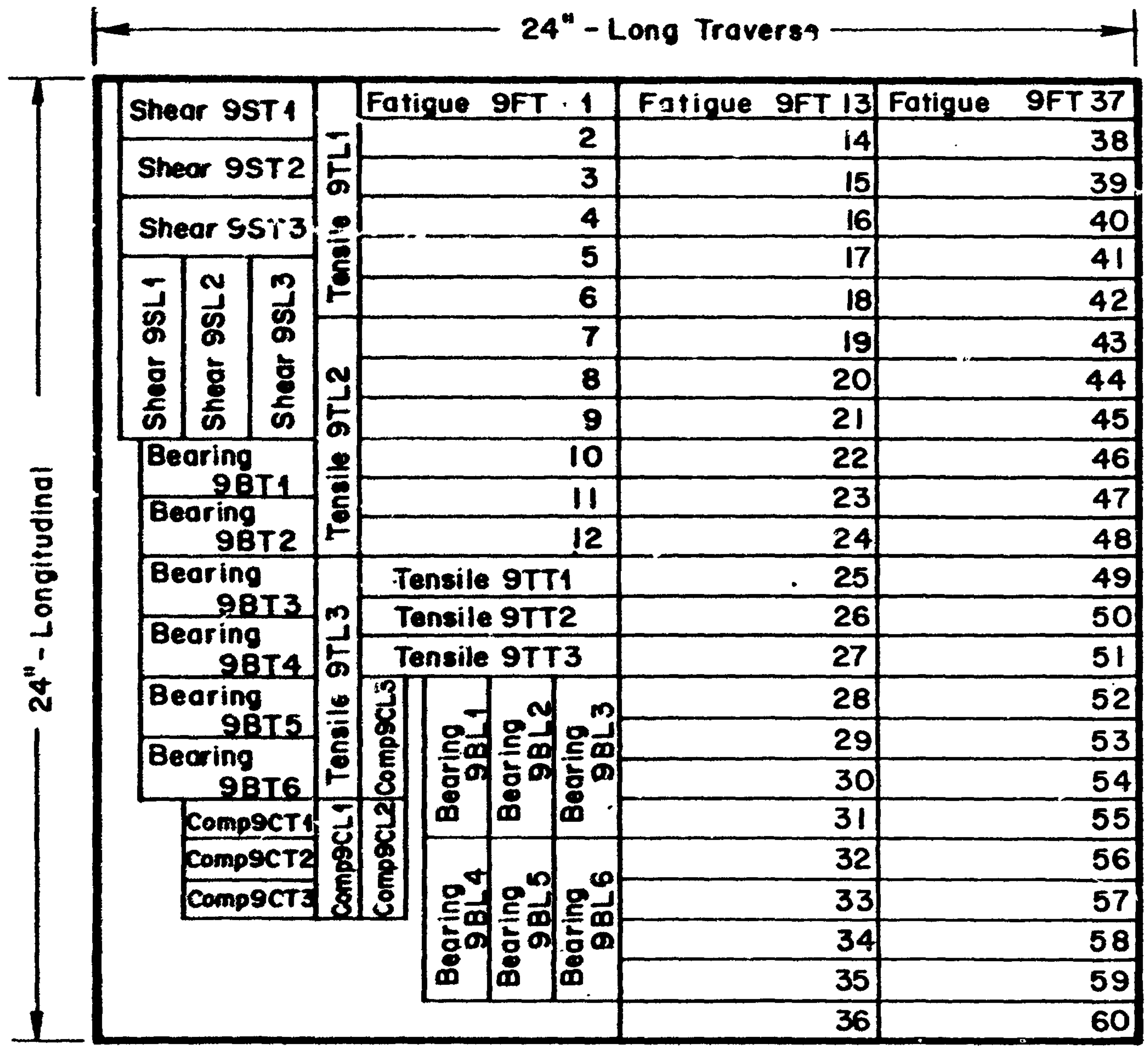


Figure 12. Location of test specimens for Ti-15V-3Cr-3Sn-3Al sheet--0.113 (P6562) inches thick.

X X X X

- Lot Number
- Type of Specimen
- Grain Direction
- Specimen No.

Specimen No.: 1, 2, 3, 4, etc.

Grain Direction:

Longitudinal	= L
Long Transverse	= T

Type of Specimen:

Tension	= T	Bearing	= B
Compression	= C	Fatigue	= F
Shear	= S		

Lot Number:

0.021"	P6562	= 1
0.023"	S8373	= 2
0.040"	S6928	= 3
0.051"	P6560	= 4
0.052"	P6562	= 5
0.056"	S8373	= 6
0.063"	S9343	= 7
0.072"	S8373	= 8
0.113"	P6562	= 9
0.116"	P6562	= 10

Specimen Configuration

The configurations of the test specimens are shown in Appendix B. Due to the limited quantity of material, it was necessary to reduce the width of the bearing specimen from 2 to 1-1/2 inches. Also, it was necessary to restrict the width of fatigue specimens to 3/4 inch. This design resulted in grip failures in the unnotched specimens. The 3/8-inch-wide reduced section was machined to 1/4-inch width for the remaining specimens.

Test Results

Tensile. The results of the tensile tests are shown in Tables 4 and 4(SI). In addition to tensile yield and ultimate strengths, elongation and modulus of elasticity values are indicated. Typical tensile stress-strain curves for each grain direction are presented in Figure 13. The tensile stress-strain curves were constructed in the same manner as those for 7149-T73 hand forgings.

Compression. The results of compression tests are shown in Tables 4 and 4(SI). Compressive modulus of elasticity values are listed in addition to compression yield strengths. Typical compressive stress-strain curves are presented in Figure 14 for each grain direction. The compressive stress-strain curves were constructed in the same manner as those for 7149-T73 hand forgings.

Shear. The results of tension-shear tests are shown in Tables 4 and 4(SI). The 0.021- and 0.023-inch-thick sheets were not tested to determine shear strength due to the anticipated instability of thin tension-shear specimens during testing. Tension-shear specimens from the 0.113-inch-thick sheet were tested by AFWAL Materials Laboratory.

Bearing. The results of the bearing tests are shown in Tables 4 and 4(SI). The 0.021- and 0.023-inch sheets were not tested to determine bearing strengths due to the anticipated instability of thin bearing specimens during testing. The bearing specimens from sheets equal to or less than 0.063-inch thick exhibited instability during testing. Excessive bending of the bearing specimen invalidated some of the test results. The ultimate loads for $e/D = 2.0$ were most frequently affected for the thinnest gages. Bearing specimens from the 0.113-inch-thick sheet were tested by AFWAL Materials Laboratory.

Fatigue. The results of axial-stress fatigue tests are presented in Tables 5 and 6. All fatigue test specimens were taken from the 0.113-inch-thick sheet. Fatigue tests were conducted only in the long transverse grain direction utilizing unnotched and notched, $K_t = 3$, specimens. Tests were conducted at three stress ratios, $R = -0.1$, $R = 0.1$, and $R = 0.5$. The fatigue specimens for the $R = 0.5$ stress ratio were tested by AFWAL Materials Laboratory. Due to a limited quantity of material, the width of fatigue specimens

TABLE 4. MECHANICAL PROPERTIES OF Ti-15V-3Cr-3Sn-3Al SOLUTION TREATED SHEET

Thickness, inches	Grain Direction	Specimen No.	Tensile Ultimate Strength, ksi	Tensile Yield Strength, ksi	Tensile Elongation, percent	Tensile Modulus, 10^3 ksi	Compressive Yield Strength, ksi	Compressive Modulus, 10^3 ksi	Ultimate Shear Strength, ksi	Bearing e/D = 1.5 Ultimate Strength, ksi	Bearing e/D = 1.5 Yield Strength, ksi	Bearing e/D = 2.0(1) Ultimate Strength, ksi	Bearing e/D = 2.0(1) Yield Strength, ksi
0.021	L	1	116.0	115.2	15.5	11.5	120.1	12.5	-	-	-	-	-
		2	116.7	115.7	16.0	11.3	119.6	12.6	-	-	-	-	-
		3	114.6	113.6	16.0	11.4	121.0	12.7	-	-	-	-	-
		Avg.	115.8	114.8	15.8	11.4	121.2	12.6	-	-	-	-	-
	LT	1	119.0	118.8	11.5	12.1	124.5	13.3	-	-	-	-	-
		2	118.6	118.2	13.0	12.2	125.7	13.3	-	-	-	-	-
		3	118.1	117.6	12.5	12.3	125.9	13.5	-	-	-	-	-
		Avg.	118.6	118.2	12.3	12.2	125.4	13.3	-	-	-	-	-
0.023	L	1	114.5	113.5	14.0	11.8	122.1	13.0	-	-	-	-	-
		2	114.7	114.0	14.0	11.6	119.4	12.8	-	-	-	-	-
		3	113.8	113.3	14.0	11.5	118.6	12.7	-	-	-	-	-
		Avg.	114.3	113.6	14.0	11.6	120.0	12.8	-	-	-	-	-
	LT	1	115.6	115.4	14.0	12.5	125.7	13.7	-	-	-	-	-
		2	118.9	118.5	12.5	12.9	125.9	13.5	-	-	-	-	-
		3	118.3	118.0	13.5	12.5	126.1	13.4	-	-	-	-	-
		Avg.	117.6	117.3	13.3	12.6	125.9	13.5	-	-	-	-	-
0.040	L	1	116.2	114.7	16.5	11.2	122.4	12.0	91.5	195.6	169.9	(2)	(2)
		2	117.3	116.3	16.5	11.2	123.7	12.1	94.1	(2)	161.2	(2)	177.4
		3	115.9	115.0	16.0	11.3	123.8	12.0	90.4	194.2	160.2	(2)	(2)
		Avg.	116.5	115.3	16.3	11.2	123.3	12.0	92.0	194.9	163.8		177.4
	LT	1	118.7	118.5	16.5	11.9	127.3	13.1	89.4	186.5	168.3	(2)	189.9
		2	118.6	118.2	16.5	12.0	127.7	13.0	90.6	220.9	170.9	(2)	170.7
		3	119.5	118.9	14.0	11.8	127.7	13.1	91.2	177.8	165.9	(2)	191.3
		Avg.	118.9	118.5	15.7	11.9	127.6	13.1	90.4	195.1	168.4		184.0
0.051	L	1	111.3	110.1	15.0	11.6	118.9	12.5	88.0	192.0	159.6	(2)	174.6
		2	111.4	110.2	15.0	11.5	119.9	12.5	85.9	192.0	162.0	(2)	172.6
		3	112.0	110.9	14.5	11.4	120.9	12.6	87.9	184.0	154.0	(2)	181.0
		Avg.	111.6	110.4	14.8	11.5	119.9	12.5	87.3	189.0	158.5		176.1
	LT	1	115.1	114.9	15.0	12.2	123.5	13.6	85.0	194.9	157.5	263.5	177.8
		2	116.0	115.6	14.5	12.2	124.8	13.6	87.0	188.5	156.3	250.8	172.2
		3	115.9	115.5	13.5	12.3	123.9	13.4	88.9	196.0	154.8	243.7	176.6
		Avg.	115.7	115.3	14.3	12.2	124.1	13.5	87.0	193.1	156.2	252.7	175.5

TABLE 4. MECHANICAL PROPERTIES OF Ti-15V-3Cr-3Sn-3Al SOLUTION TREATED SHEET (Continued)

Thickness, inches	Grain Direction	Speci-men No.	Tensile				Compressive		Ultimate Shear Strength, ksi	Bearing			
										e/D = 1.5		e/D = 2.0(1)	
			Ultimate Strength, ksi	Yield Strength, ksi	Elong-ation, percent	Modulus, 10^3 ksi	Yield Strength, ksi	Modulus, 10^3 ksi		Ultimate Strength, ksi	Yield Strength, ksi	Ultimate Strength, ksi	Yield Strength, ksi
0.052	L	1	113.6	113.0	13.0	11.2	123.6	12.2	88.9	198.9	164.1	(2)	175.0
		2	113.2	112.2	14.5	11.2	124.5	12.3	91.3	205.7	162.7	(2)	184.8
		3	114.6	113.6	15.0	11.1	124.4	12.3	90.4	206.4	159.8	261.1	177.9
		Avg.	113.8	112.9	14.2	11.2	124.2	12.3	90.2	203.7	162.2	261.1	179.2
	LT	1	117.4	117.0	16.0	12.2	126.8	13.1	90.1	204.5	167.9	276.7	175.9
		2	118.5	118.1	13.5	12.1	126.8	13.1	90.9	203.4	157.9	250.0	175.0
		3	118.6	117.9	15.0	12.1	127.2	13.1	90.4	203.4	160.9	254.5	170.5
		Avg.	118.2	117.7	14.8	12.1	126.9	13.1	90.5	203.8	162.2	260.4	173.8
0.056	L	1	112.8	112.6	15.5	11.7	119.7	12.8	88.6	196.5	155.6	253.5	172.7
		2	113.0	112.3	16.0	11.8	119.7	12.7	92.4	196.2	157.3	(2)	172.7
		3	113.6	112.9	16.5	11.6	119.9	12.7	88.9	195.8	179.4	(2)	174.8
		Avg.	113.1	112.6	16.0	11.7	119.8	12.7	90.0	196.2	164.1	253.5	173.4
	LT	1	117.2	116.9	13.5	12.7	126.0	13.7	87.6	195.8	152.1	264.8	176.1
		2	117.4	117.1	13.0	12.9	126.2	13.9	85.5	195.4	154.9	227.1	182.4
		3	118.7	118.4	12.0	12.7	127.6	13.8	87.6	195.3	157.4	278.0	171.0
		Avg.	117.8	117.5	12.8	12.8	126.6	13.8	86.9	195.5	154.8	256.6	176.5
0.063	L	1	112.3	111.7	15.5	11.5	119.8	12.2	90.7	197.9	154.9	(2)	171.8
		2	111.1	110.6	17.0	11.4	119.8	12.2	89.2	197.9	156.4	251.5	170.2
		3	112.0	111.7	17.5	11.4	119.7	12.2	88.6	199.4	162.6	(2)	171.8
		Avg.	111.8	111.3	16.7	11.4	119.8	12.2	89.5	198.4	158.0	251.5	171.3
	LT	1	115.2	114.9	16.5	12.1	122.1	13.2	89.1	199.4	156.4	252.1	180.7
		2	114.9	114.6	16.5	12.3	122.0	13.1	89.7	199.4	161.0	236.2	182.5
		3	113.6	110.8	18.0	12.2	121.9	13.1	94.8	199.4	159.5	262.3	174.5
		Avg.	114.6	113.4	17.0	12.2	122.0	13.1	91.2	199.4	159.0	250.2	179.2

TABLE 4. MECHANICAL PROPERTIES OF Ti-15V-3Cr-3Sn-3Al SOLUTION TREATED SHEET (Concluded)

Thickness, inches	Grain Direction	Specimen No.	Tensile Ultimate Strength, ksi	Tensile Yield Strength, ksi	Tensile Elongation, percent	Tensile Modulus, 10^3 ksi	Compressive Yield Strength, ksi	Compressive Modulus, 10^3 ksi	Ultimate Shear Strength, ksi	Bearing e/D = 1.5 Ultimate Strength, ksi	Bearing e/D = 1.5 Yield Strength, ksi	Bearing e/D = 2.0(1) Ultimate Strength, ksi	Bearing e/D = 2.0(1) Yield Strength, ksi
0.072	L	1	113.4	112.8	16.5	11.4	118.0	12.2	91.1	197.3	155.9	252.7	180.4
		2	113.0	112.1	17.0	11.0	117.7	12.1	90.3	201.1	157.1	258.7	175.3
		3	113.4	112.5	17.5	11.0	118.3	12.2	89.0	200.8	157.9	260.1	173.5
		Avg.	113.3	112.5	17.0	11.1	118.0	12.2	90.1	199.7	157.0	257.2	176.4
	LT	1	117.5	117.5	13.5	12.2	124.0	13.2	90.4	199.7	160.3	256.3	184.4
		2	117.8	117.2	13.5	12.3	123.5	13.3	87.8	198.5	154.9	260.9	177.6
		3	117.8	117.2	13.0	12.2	123.6	13.2	89.0	201.6	161.2	224.6	180.9
		Avg.	117.7	117.3	13.3	12.2	123.7	13.2	89.1	199.9	158.8	247.3	181.0
0.113(4)	L	1	113.7	112.8	16.5	11.4	116.4	12.7	88.4	201.3	153.5	267.0	200.3
		2	114.6	113.9	16.0	11.5	115.8	12.8	89.0	205.2	166.8	(3)	(3)
		3	114.1	113.0	16.0	11.6	113.6	12.8	87.9	202.8	157.5	(3)	(3)
		Avg.	114.1	113.2	16.2	11.5	115.3	12.8	88.4	203.1	159.3	267.0	200.3
	LT	1	119.1	115.1	15.0	12.7	120.4	13.8	86.1	200.7	163.7	268.7	200.6
		2	120.0	119.3	13.0	12.9	120.5	13.7	87.3	198.4	165.3	269.9	200.7
		3	119.9	119.6	12.0	13.0	120.9	13.7	90.1	206.1	167.5	266.6	198.5
		Avg.	119.7	118.0	13.3	12.9	120.6	13.7	87.8	201.7	165.5	268.4	199.9
0.116	L	1	112.0	111.4	19.0	11.6	114.2	12.8	94.0	200.3	168.2	263.7	184.9
		2	112.7	112.0	18.0	11.7	113.7	12.8	93.8	200.0	160.6	262.0	186.3
		3	113.8	113.4	16.5	11.7	114.1	12.8	93.9	200.0	161.6	262.9	179.7
		Avg.	112.8	112.3	17.8	11.7	114.0	12.8	93.9	200.1	163.5	262.9	183.6
	LT	1	117.6	117.1	14.0	12.8	121.0	13.8	90.8	202.7	167.9	263.5	190.4
		2	118.0	117.5	13.5	12.9	121.7	13.9	91.1	202.1	167.1	263.1	182.6
		3	118.2	117.7	14.0	12.9	121.1	13.7	91.1	200.7	159.2	261.7	188.4
		Avg.	117.9	117.4	13.8	12.9	121.3	13.8	91.0	201.8	164.7	263.1	187.1

(1) Specimen numbers for e/D = 2.0 were 4 through 6.
(2) Excessive bending of specimen.
(3) Specimen ruined due to machining error.
(4) Tension-shear and bearing specimens were tested by AFWAL Materials Laboratory.

TABLE 4 (SI). MECHANICAL PROPERTIES OF TI-15V-3CR-3SN-3AL SOLUTION TREATED SHEET

Thickness, mm	Grain Direction	Speci-men No.	Tensile Ultimate Strength, MPa	Tensile Yield Strength, MPa	Tensile Elong-ation, Percent	Tensile Modulus, GPa	Compressive Yield Strength, MPa	Compressive Modulus, GPa	Ultimate Shear Strength, MPa	Bearing e/D = 1.5 Ultimate Strength, MPa	Bearing e/D = 1.5 Yield Strength, MPa	Bearing e/D = 2.0(1) Ultimate Strength, MPa	Bearing e/D = 2.0(1) Yield Strength MPa
0.53	L	1	799.8	794.3	15.5	79.3	828.1	86.2	-	-	-	-	-
		2	804.6	797.8	16.0	77.9	824.6	86.9	-	-	-	-	-
		3	790.2	783.3	16.0	78.6	834.3	87.6	-	-	-	-	-
		Avg.	798.2	791.8	15.8	78.6	829.0	86.9					
	LT	1	820.5	819.1	11.5	83.4	858.4	91.7	-	-	-	-	-
		2	817.7	815.0	13.0	84.1	866.7	91.7	-	-	-	-	-
		3	814.3	810.8	12.5	84.8	868.1	93.1	-	-	-	-	-
		Avg.	817.5	815.0	12.3	84.1	864.4	92.2					
0.58	L	1	789.5	782.6	14.0	81.4	841.9	89.6	-	-	-	-	-
		2	790.8	786.0	14.0	80.0	923.3	88.2	-	-	-	-	-
		3	784.6	781.2	14.0	79.3	817.7	87.6	-	-	-	-	-
		Avg.	788.3	783.3	14.0	80.2	827.6	88.5					
	LT	1	797.1	795.7	14.0	86.2	866.7	94.5	-	-	-	-	-
		2	819.8	817.0	12.5	88.9	868.1	93.1	-	-	-	-	-
		3	815.7	813.6	13.5	86.2	869.4	92.4	-	-	-	-	-
		Avg.	810.9	808.8	13.3	87.1	868.1	93.3					
1.04	L	1	801.2	790.8	16.5	77.2	843.9	82.7	630.9	1348.7	1171.5	(2)	1165.2
		2	808.8	801.9	16.5	77.2	852.9	83.4	648.8	(2)	1111.5	(2)	1223.2
		3	799.1	792.9	16.0	77.9	853.6	82.7	623.3	1339.0	1104.6	(2)	1153.5
		Avg.	803.0	795.2	16.3	77.4	850.1	82.9	634.3	1343.8	1129.2		1180.6
	LT	1	814.4	817.0	16.5	82.0	-	90.3	616.4	1285.9	1160.4	(2)	1309.4
		2	817.7	815.0	16.5	82.7	880.5	89.6	624.7	1523.1	1178.4	(2)	1177.0
		3	824.0	819.8	14.0	81.4	880.5	90.3	628.8	1225.9	1143.9	(2)	1319.0
		Avg.	818.7	817.3	15.7	82.0	880.5	90.1	623.3	1345.0	1160.9		1268.5

TABLE 4 (SI). MECHANICAL PROPERTIES OF TI-15V-3CR-3SN-3AL SOLUTION TREATED SHEET (Continued)

Thickness, mm	Grain Direction	Speci-men No.	Tensile Ultimate Strength, MPa	Tensile Yield Strength, MPa	Tensile Elong-ation, Percent	Tensile Modulus, GPa	Compressive Yield Strength, MPa	Compressive Modulus, GPa	Ultimate Shear Strength, MPa	Bearing e/D = 1.5 Ultimate Strength, MPa	Bearing e/D = 1.5 Yield Strength, MPa	Bearing e/D = 2.0(1) Ultimate Strength, MPa	Bearing e/D = 2.0(1) Yield Strength, MPa
1.30	L	1	767.4	759.1	15.0	80.0	819.8	86.2	606.8	1323.3	1100.4	(2)	1203.9
		2	768.1	759.8	15.0	79.3	826.7	86.2	592.3	1323.8	1117.0	(2)	1190.1
		3	772.2	764.6	14.5	78.6	833.6	86.9	606.1	1268.7	1061.8	(2)	1248.0
		Avg.	769.2	761.2	14.8	79.3	826.7	86.4	601.7	1305.3	1093.1		1214.0
	LT	1	793.5	792.2	15.0	84.1	851.5	93.8	586.1	1343.8	1086.0	1816.8	1225.9
		2	799.8	797.0	14.5	84.1	860.5	93.8	599.9	1299.7	1077.7	1729.3	1187.3
		3	799.1	795.4	13.5	84.8	854.3	92.4	613.0	1351.4	1067.3	1680.3	1217.6
		Avg.	797.5	795.2	14.3	84.3	855.4	93.3	599.7	1331.6	1077.0	1742.1	1210.3
1.32	L	1	783.3	779.1	13.0	77.2	852.2	84.1	613.0	1371.4	1131.5	(2)	1206.6
		2	780.5	773.6	14.5	77.2	858.4	84.8	629.5	1418.3	1121.8	(2)	1274.2
		3	790.2	783.3	15.0	76.5	857.7	84.8	623.3	1423.1	1101.8	1800.3	1226.6
		Avg.	784.7	778.7	14.2	77.0	856.1	84.6	621.9	1404.3	1118.4	1800.3	1235.8
	LT	1	809.5	806.7	16.0	84.1	874.3	90.3	621.2	1410.0	1157.7	1907.8	1212.8
		2	817.0	814.3	13.5	83.4	874.3	90.3	626.8	1402.4	1088.7	1723.8	1206.6
		3	817.7	812.9	15.0	83.4	877.0	90.3	623.3	1402.4	1109.4	1754.8	1175.6
		Avg.	814.7	811.3	14.8	83.6	875.2	90.3	623.8	1404.9	1118.6	1795.5	1198.3
1.42	L	1	777.8	776.4	15.5	80.7	825.3	88.2	610.9	1354.9	1072.9	1747.9	1190.8
		2	779.1	774.3	16.0	81.4	825.3	87.6	637.1	1352.8	1084.6	1441.7	1190.8
		3	783.3	776.4	16.5	80.0	826.7	87.6	613.0	1350.0	1237.0	1562.4	1205.2
		Avg.	780.1	776.4	16.0	80.7	825.8	87.8	620.3	1352.6	1131.5	1584.0	1195.6
	LT	1	808.1	806.0	13.5	87.6	868.8	94.5	604.0	1350.0	1048.7	1825.8	1214.2
		2	809.5	807.4	13.0	88.9	870.1	95.8	589.5	1347.3	1068.0	1565.8	1257.6
		3	818.4	816.4	12.0	87.6	879.8	95.2	604.0	1346.6	1085.3	1916.8	1179.0
		Avg.	812.0	809.9	12.8	88.0	872.9	95.2	599.2	1348.0	1067.3	1769.5	1216.9
1.60	L	1	774.3	770.2	15.5	79.3	826.0	84.1	625.4	1364.5	1068.0	1586.5	1184.6
		2	766.0	762.6	17.0	78.6	826.0	84.1	615.0	1364.5	1078.4	1734.1	1173.5
		3	772.2	770.2	17.5	78.6	825.3	84.1	610.9	1374.9	1121.1	1596.9	1184.6
		Avg.	770.8	767.7	16.7	78.8	825.8	84.1	617.1	1368.0	1089.2	1639.2	1180.9
	LT	1	794.3	792.2	16.5	83.4	841.9	91.0	614.3	1374.9	1078.4	1738.2	1245.9
		2	792.2	790.2	16.5	84.8	841.2	90.3	618.5	1374.9	1110.1	1628.6	1258.3
		3	783.3	764.0	18.0	84.1	840.5	90.3	653.6	1374.9	1099.8	1808.6	1203.2
		Avg.	789.9	782.1	17.0	84.1	841.2	90.5	628.8	1374.9	1096.1	1725.1	1235.8

TABLE 4 (SI). MECHANICAL PROPERTIES OF TI-15V-3CR-3SN-3AL SOLUTION TREATED SHEET (Concluded)

Thickness, mm	Grain Direction	Specimen No.	Tensile Ultimate Strength, MPa	Tensile Yield Strength, MPa	Tensile Elongation, Percent	Tensile Modulus, GPa	Compressive Yield Strength, MPa	Compressive Modulus, GPa	Ultimate Shear Strength, MPa	Bearing e/D = 1.5 Ultimate Strength, MPa	Bearing e/D = 1.5 Yield Strength, MPa	Bearing e/D = 2.0(1) Ultimate Strength, MPa	Bearing e/D = 2.0(1) Yield Strength, MPa
1.83	L	1	781.9	777.8	16.5	78.6	813.6	84.1	628.1	1360.4	1074.9	1742.4	1243.8
		2	779.1	772.9	17.0	75.8	811.5	83.4	622.6	1386.6	1083.2	1783.7	1208.7
		3	781.9	775.7	17.5	75.8	815.7	84.1	613.6	1384.5	1088.7	1793.4	1196.3
		Avg.	781.0	775.5	17.0	76.7	813.6	83.9	621.4	1377.2	1082.3	1773.2	1216.3
	LT	1	810.2	810.2	13.5	84.1	855.0	91.0	623.3	1376.9	1105.3	1767.2	1271.4
		2	812.2	808.1	13.5	84.8	851.5	91.7	605.4	1368.6	1068.0	1798.9	1224.6
		3	812.2	808.1	13.0	84.1	852.2	91.0	613.6	1390.0	1111.5	1548.6	1247.3
		Avg.	811.5	808.8	13.3	84.3	852.9	91.2	614.1	1378.5	1094.9	1704.9	1247.8
2.87(4)	L	1	784.0	777.8	16.5	78.6	802.6	87.6	609.5	1388.0	1058.4	1841.0	1381.1
		2	790.2	785.3	16.0	79.3	798.4	88.3	613.6	1414.8	1150.1	(3)	(3)
		3	786.7	779.3	16.0	80.0	783.3	88.3	606.1	1398.3	1086.0	(3)	(3)
		Avg.	787.0	780.7	16.2	79.3	794.8	88.1	609.7	1400.4	1098.2	1841.0	1381.1
	LT	1	821.2	793.6	15.0	87.6	830.2	95.2	593.6	1383.8	1128.7	1852.7	1383.1
		2	827.4	822.6	13.0	88.9	830.8	96.5	601.9	1368.0	1139.7	1861.0	1383.8
		3	826.7	824.6	12.0	89.6	833.6	94.5	621.2	1421.0	1154.9	1838.9	1368.6
		Avg.	825.1	813.6	13.3	88.7	831.5	94.7	605.6	1390.9	1141.1	1850.9	1378.5
2.95	L	1	772.2	768.1	19.0	80.0	787.4	88.2	648.1	1381.1	1159.7	1818.2	1274.9
		2	777.1	772.2	18.0	80.7	784.0	88.2	646.8	1379.0	1107.3	1806.5	1284.5
		3	784.6	781.9	16.5	80.7	786.7	88.2	647.4	1379.0	1114.2	1812.7	1239.0
		Avg.	778.0	774.1	17.8	80.5	780.0	88.2	647.4	1379.7	1127.1	1812.5	1266.1
	LT	1	810.8	807.4	14.0	88.2	834.3	95.2	626.1	1397.6	1157.7	1816.8	1312.8
		2	813.6	810.2	13.5	88.9	839.1	95.8	628.1	1393.5	1152.2	1814.1	1259.0
		3	815.0	811.5	14.0	88.9	835.0	94.5	628.1	1383.8	1097.7	1811.3	1299.0
		Avg.	813.1	809.7	13.8	88.7	836.1	95.2	627.4	1391.6	1135.9	1814.1	1290.3

(1) Specimen number for e/D - 2.0 were 4 through 5.
(2) Excessive bending of specimen.
(3) Specimen ruined due to machining error.
(4) Tension-shear and bearing specimens for 2.9 mm were tested by AFWAL Materials Laboratory.

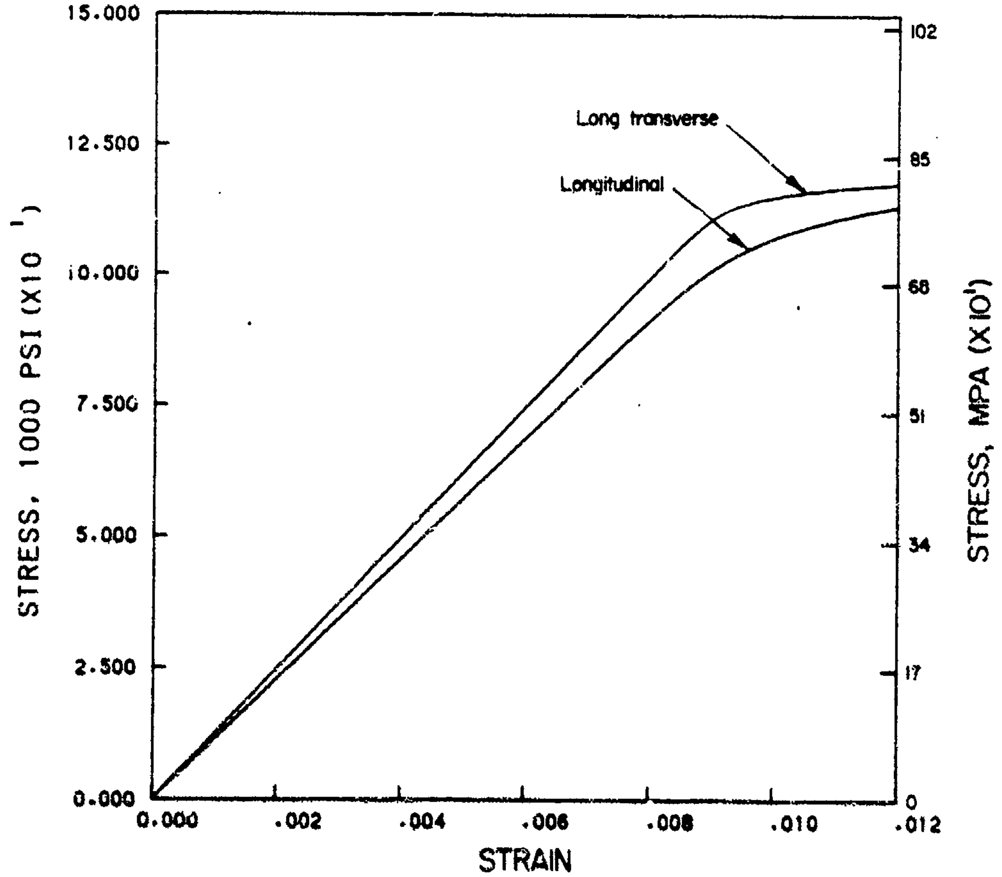


Figure 13. Typical tensile stress-strain curves for Ti-15V-3Cr-3Sn-3Al solution treated sheet.

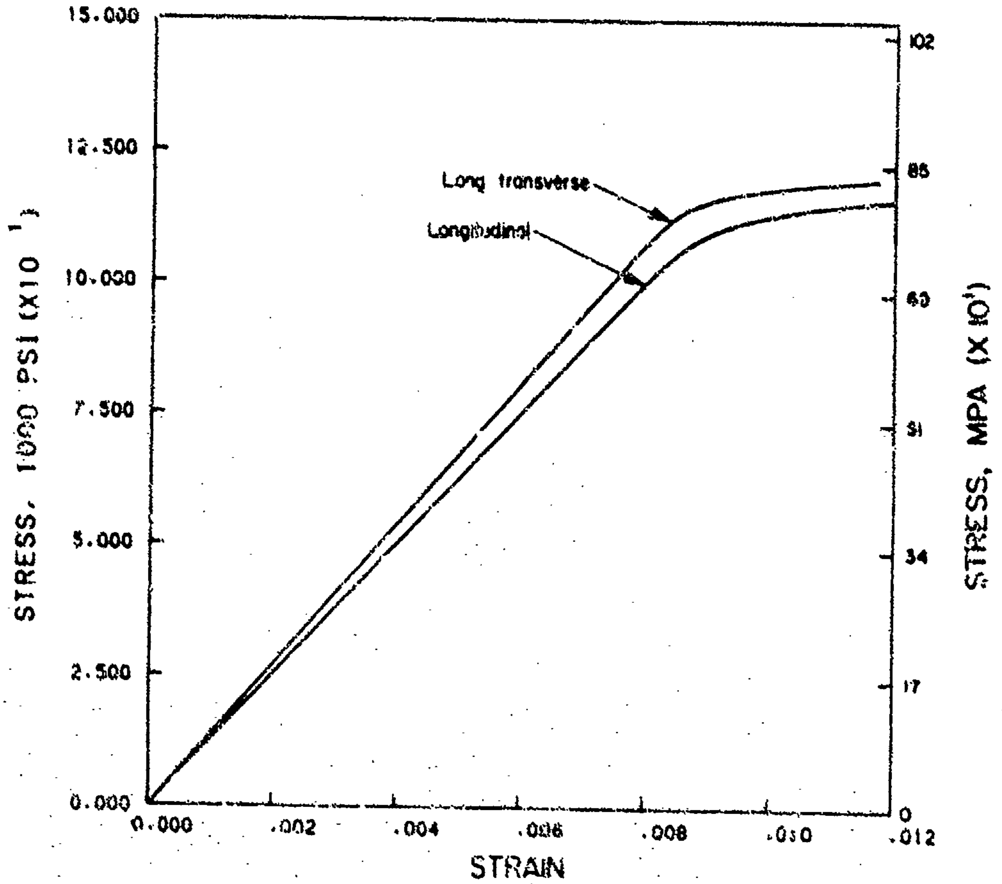


Figure 14. Typical compressive stress-strain curves for Ti-15V-3Cr-3Sn-3Al solution treated sheet.

TABLE 5. UNNOTCHED FATIGUE DATA FOR Ti-15V-3Cr-3Sn-3Al SOLUTION TREATED SHEET--LONG TRANSVERSE DIRECTION

Specimen ID	Maximum Stress ksi (MPa)	R-ratio	Cycles to Failure
9FT29	80.0 (551.6)	-0.1	19,150
9FT23	70.0 (482.7)	-0.1	48,650
9FT27	70.0 (482.7)	-0.1	36,110
9FT37	65.0 (448.2)	-0.1	56,140
9FT31	65.0 (448.2)	-0.1	188,280
9FT33	62.5 (430.9)	-0.1	DNF (1)
9FT39	62.5 (430.9)	-0.1	DNF
9FT35	60.0 (413.7)	-0.1	112,860
9FT25	60.0 (413.7)	-0.1	DNF
9FT13	105.0 (724.0)	+0.1	8,500
9FT15	105.0 (724.0)	+0.1	14,780
9FT11	95.0 (655.0)	+0.1	27,260
9FT3	80.0 (551.6)	+0.1	46,290
9FT1	80.0 (551.6)	+0.1	55,000
9FT5	70.0 (482.7)	+0.1	68,330
9FT9	60.0 (413.7)	+0.1	111,010
9FT7	60.0 (413.7)	+0.1	- (2)
9FT19	55.0 (379.2)	+0.1	- (2)
9FT17	55.0 (379.2)	+0.1	- (2)
9FT21	45.0 (310.3)	+0.1	DNF
9FT53	125.0 (861.9)	+0.5 (4)	500 (3)
9FT55	122.5 (844.6)	+0.5	7,100
9FT51	120.0 (827.4)	+0.5	44,400
9FT49	115.0 (792.9)	+0.5	4,872,300
9FT59	112.5 (775.7)	+0.5	DNF
9FT57	110.0 (758.5)	+0.5	DNF
9FT47	100.0 (689.5)	+0.5	DNF
9FT43	90.0 (620.6)	+0.5	- (2)
9FT41	90.0 (620.6)	+0.5	- (2)
9FT45	90.0 (620.6)	+0.5	DNF

---

(1) DNF--did not fail; test ran to 10,000,000 cycles and stopped.

(2) Failed in grips.

(3) Cycle count outside of 10^3-10^7. Not plotted.

(4) Stress ratio, R = + 0.5, tested by AFWAL Materials Laboratory.

TABLE 6. NOTCHED, K_t = 3, FATIGUE DATA FOR Ti-15V-3Cr-3Sn-3Al SOLUTION TREATED SHEET--LONG TRANSVERSE DIRECTION

Specimen ID	Maximum Stress ksi (MPa)	R-ratio	Cycles to Failure
9FT24	50.0 (344.8)	-0.1	8,450
9FT22	40.0 (275.8)	-0.1	17,110
9FT26	30.0 (206.9)	-0.1	26,430
9FT28	30.0 (206.9)	-0.1	33,350
9FT32	20.0 (137.9)	-0.1	86,440
9FT30	20.0 (137.9)	-0.1	94,320
9FT34	15.0 (103.4)	-0.1	248,180
9FT38	15.0 (103.4)	-0.1	DNF (1)
9FT36	10.0 (69.0)	-0.1	DNF
9FT40	10.0 (69.0)	-0.1	DNF
9FT4	60.0 (413.7)	+0.1	6,090
9FT2	60.0 (413.7)	+0.1	7,110
9FT8	40.0 (275.8)	+0.1	20,740
9FT6	40.0 (275.8)	+0.1	24,400
9FT10	25.0 (172.4)	+0.1	78,420
9FT12	25.0 (172.4)	+0.1	79,490
9FT18	20.0 (137.9)	+0.1	154,070
9FT16	20.0 (137.9)	+0.1	221,620
9FT14	15.0 (103.4)	+0.1	DNF
9FT20	15.0 (103.4)	+0.1	DNF
9FT58	90.0 (620.6)	+0.5 (2)	7,800
9FT56	80.0 (551.6)	+0.5	10,100
9FT54	70.0 (482.7)	+0.5	14,200
9FT52	65.0 (448.2)	+0.5	19,600
9FT42	60.0 (413.7)	+0.5	18,000
9FT44	50.0 (344.8)	+0.5	38,700
9FT46	40.0 (275.8)	+0.5	68,300
9FT50	35.0 (241.3)	+0.5	114,600
9FT60	32.5 (224.1)	+0.5	131,900
9FT48	30.0 (206.9)	+0.5	DNF

(1) DNF--did not fail; test ran to 10,000,000 cycles and stopped.

(2) Stress ratio, R = + 0.5, tested by AFWAL Materials Laboratory.

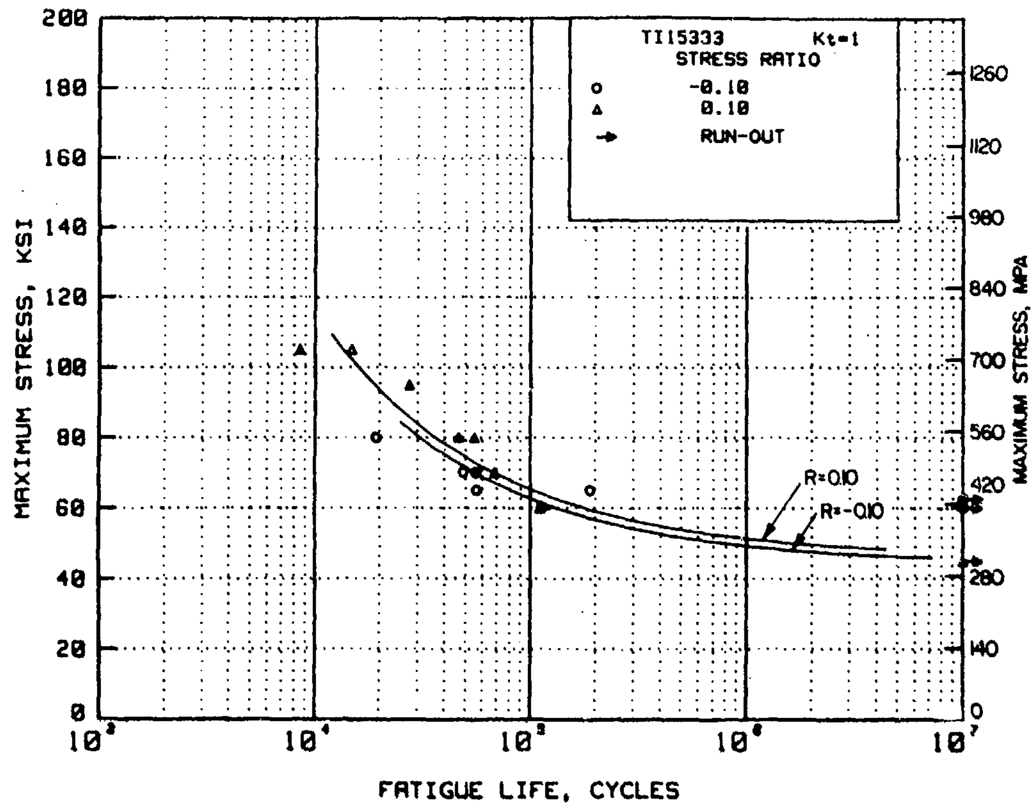


Figure 15. Unnotched axial-stress S/N curves for 0.113 inch thick Ti-15V-3Cr-3Sn-3Al solution treated sheet--long transverse grain direction.

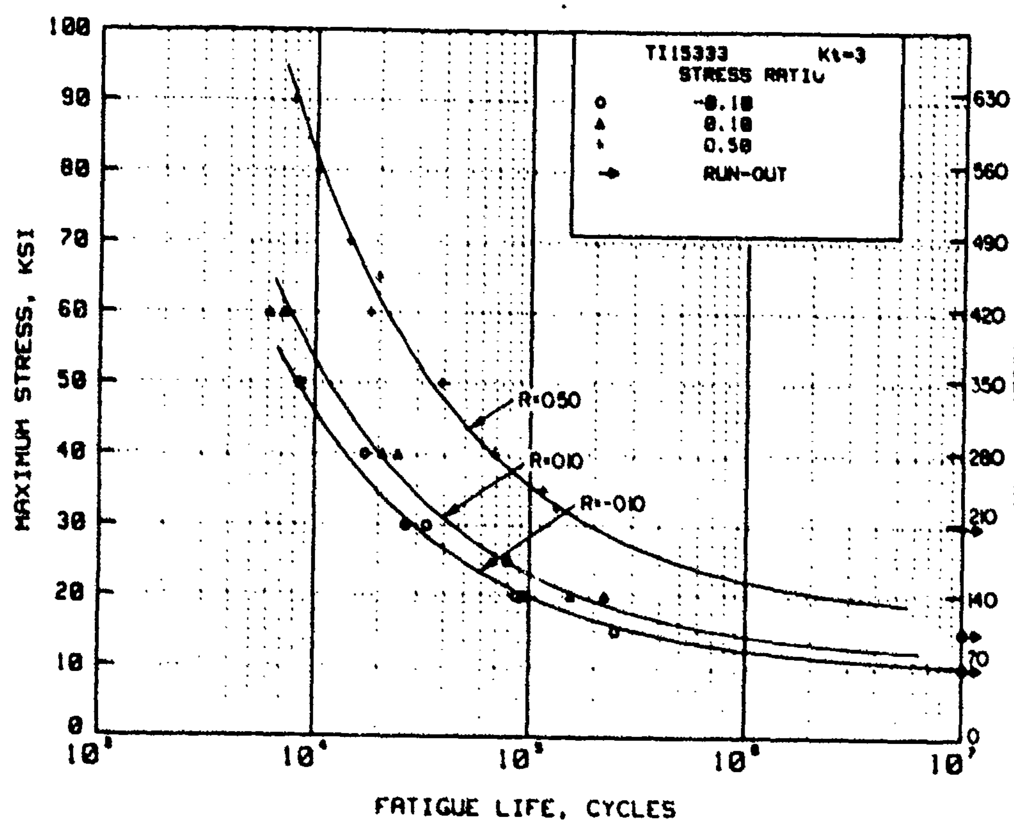


Figure 16. Notched axial-stress S/N curves for 0.113 inch thick Ti-15V-3Cr-3Sn-3Al solution treated sheet --long transverse grain direction.

was restricted to 3/4 inch. This design resulted in a tendency for grip failures for the unnotched specimens. The 3/8-inch wide reduced section was machined to 1/4-inch width for the remaining specimens. The fatigue data were analyzed in accordance with Section 9.3.4 of MIL-HDBK-5 and S/N curves in Figures 15 and 16 constructed accordingly. For the unnotched, R = +0.5 condition, only four test failures were obtained; consequently, those data were excluded from the analysis and an S/N curve for R = +0.5 was not presented.

15-5PH (H935) Corrosion Resistant Steel Castings

Background

Alloy 15-5PH precipitation hardening corrosion resistant steel castings are similar to 17-4PH castings. However, 15-5PH castings are reported to exhibit a more uniform microstructure containing less delta-ferrite. The improved microstructure, compared to 17-4PH, allegedly results in more consistent mechanical properties. Also, 15-5PH is reported to be more resistant to stress-corrosion cracking. Due to the increasing use of 15-5PH castings, it was desirable to determine the mechanical properties for this product so that design values can be subsequently determined.

Material

This alloy can be heat treated to various strength ranges by varying the aging temperature. The H935 condition which provides a tensile strength of 170-200 ksi was selected for evaluation. The Air Force supplied nine different casting configurations, Figures 17 through 25, which were suitable for the removal of various types of test specimens. The castings were produced by Arwood Corporation, Bescast, Inc., and Hemet Steel Casting Company. The Arwood and Bescast castings had received the following heat treatment by the supplier: homogenize at 2100 F for 1-1/2 hours, gas quench, solution treat at 1900 F for 1-1/2 hours, oil quench, and age at 935 F. The Hemet castings were reheat treated by the AFWAL Materials Laboratory using the same heat treat procedure except for air cooling following exposure to the homogenization temperature. (After completion of this test program, comparison revealed no significant differences in the mechanical properties of castings heat treated by the suppliers and those heat treated by the AFWAL Materials Laboratory.) The above heat treatment conforms to the procedure specified in AMS 5400. The composition limits for 15-5PH castings as specified in AMS 5400 is as follows:

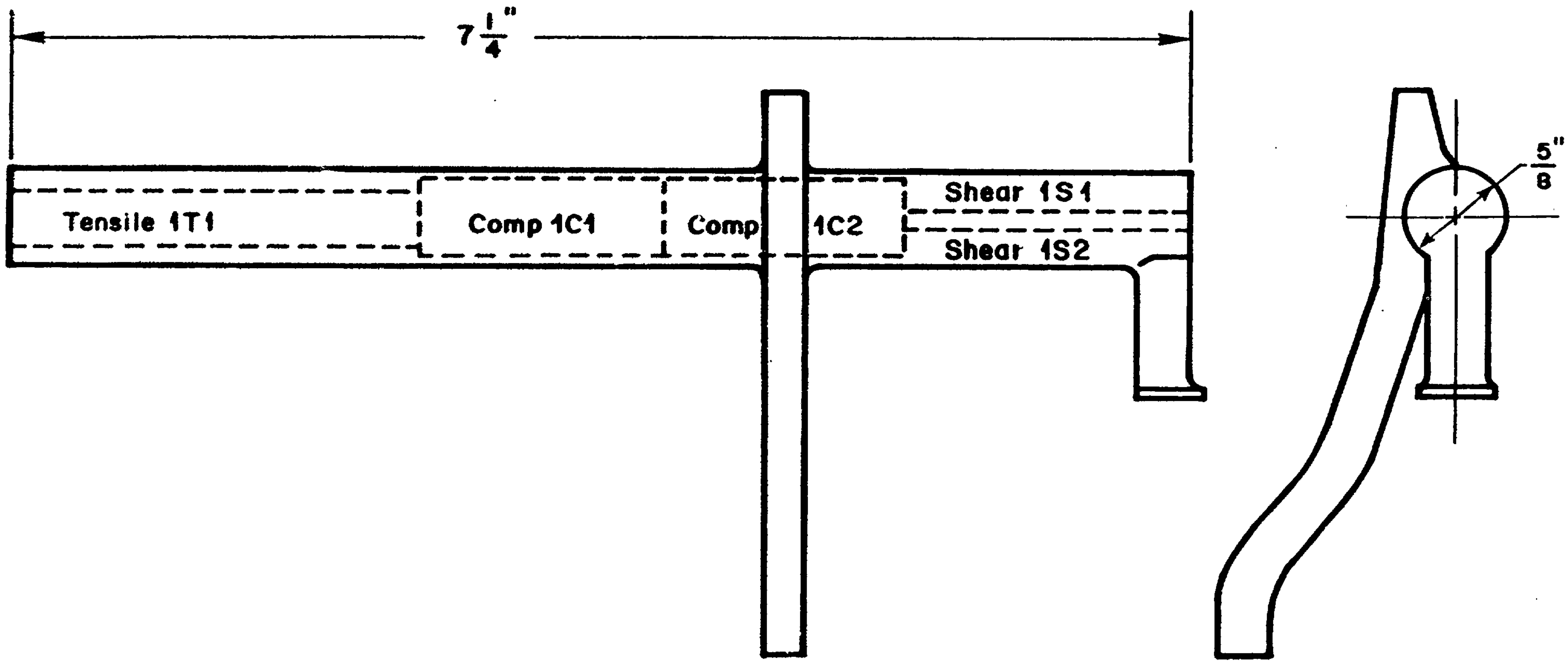
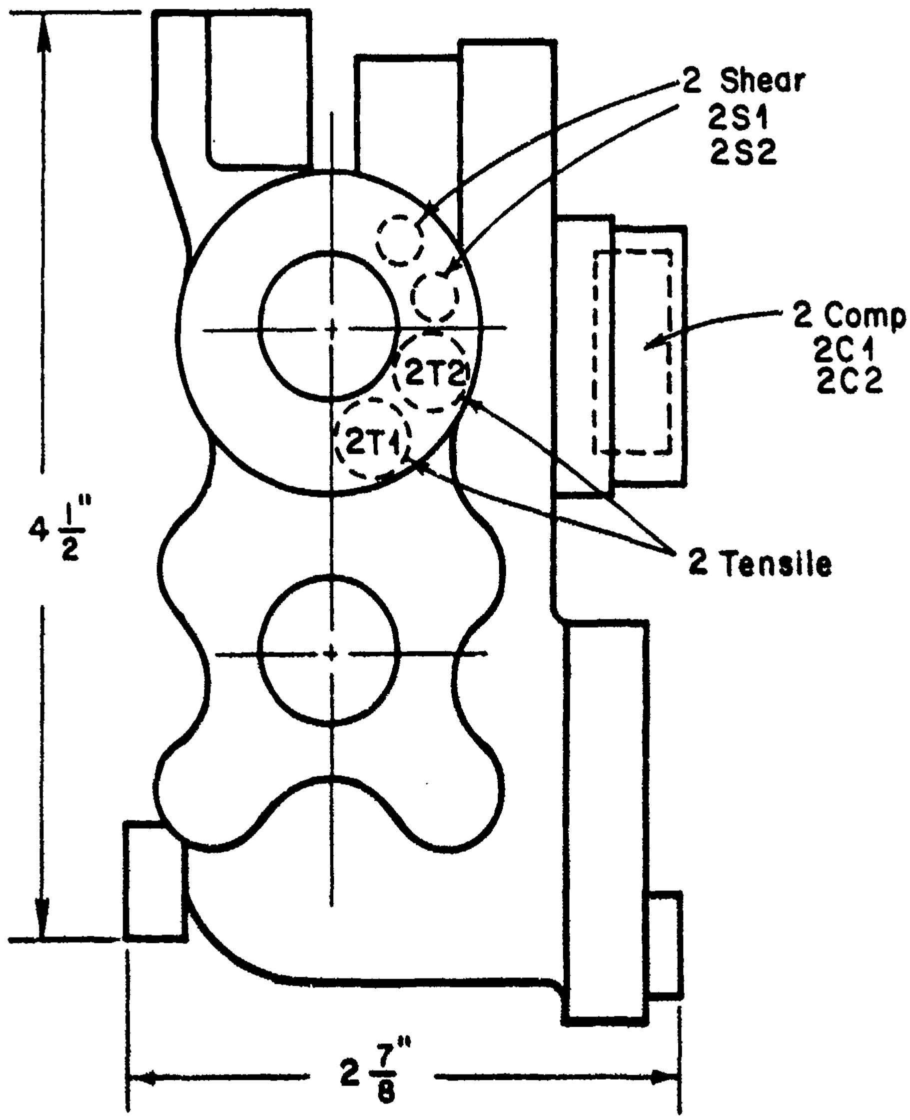


Figure 17. Location of test specimens for 15-5PH (H935) shaft casting.



(Side View)

Figure 18. Location of test specimens for 15-5PH (H925) valve body casting.

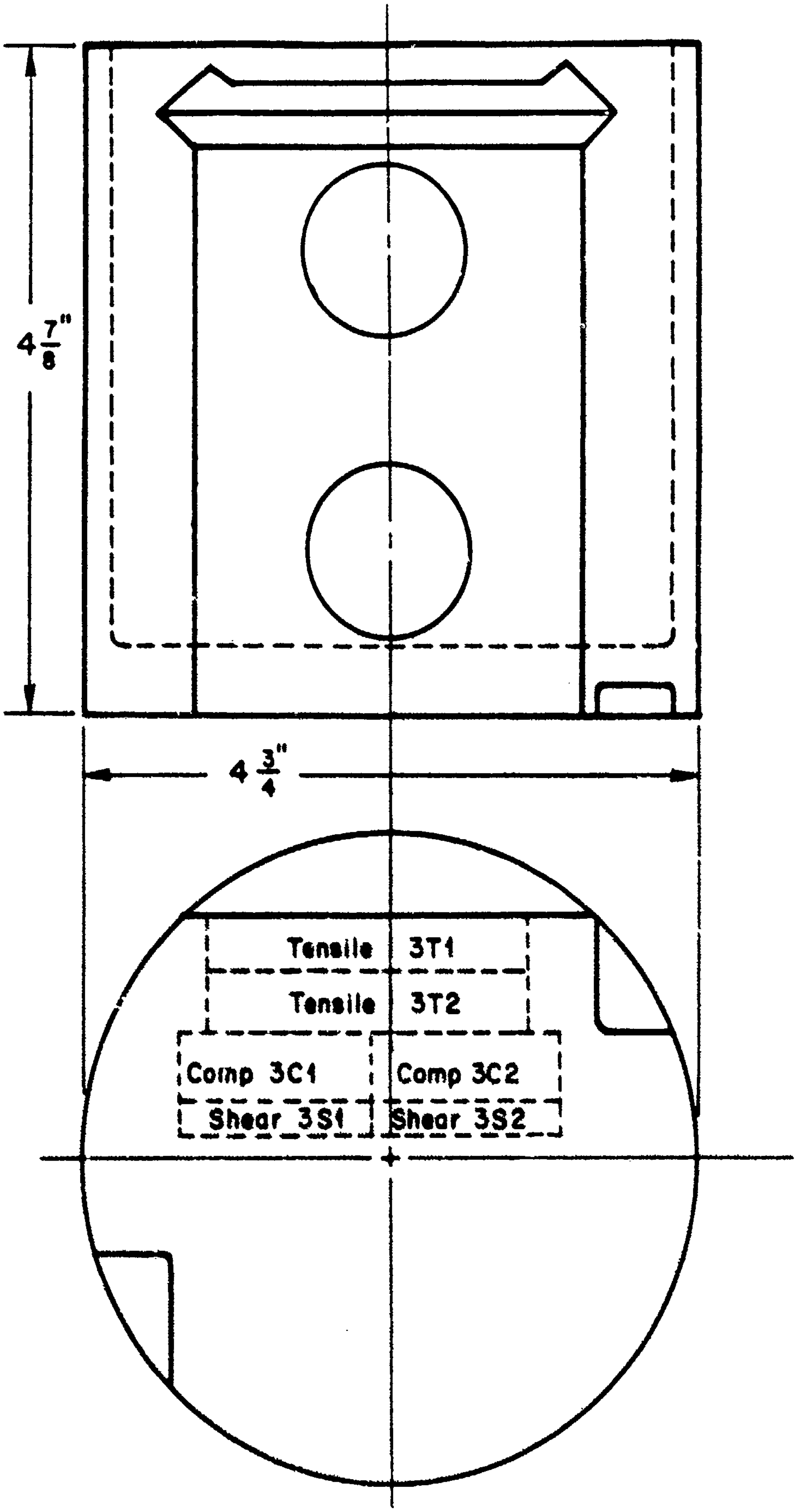


Figure 19. Location of test specimens for 15-5PH (H925) cylinder casting.

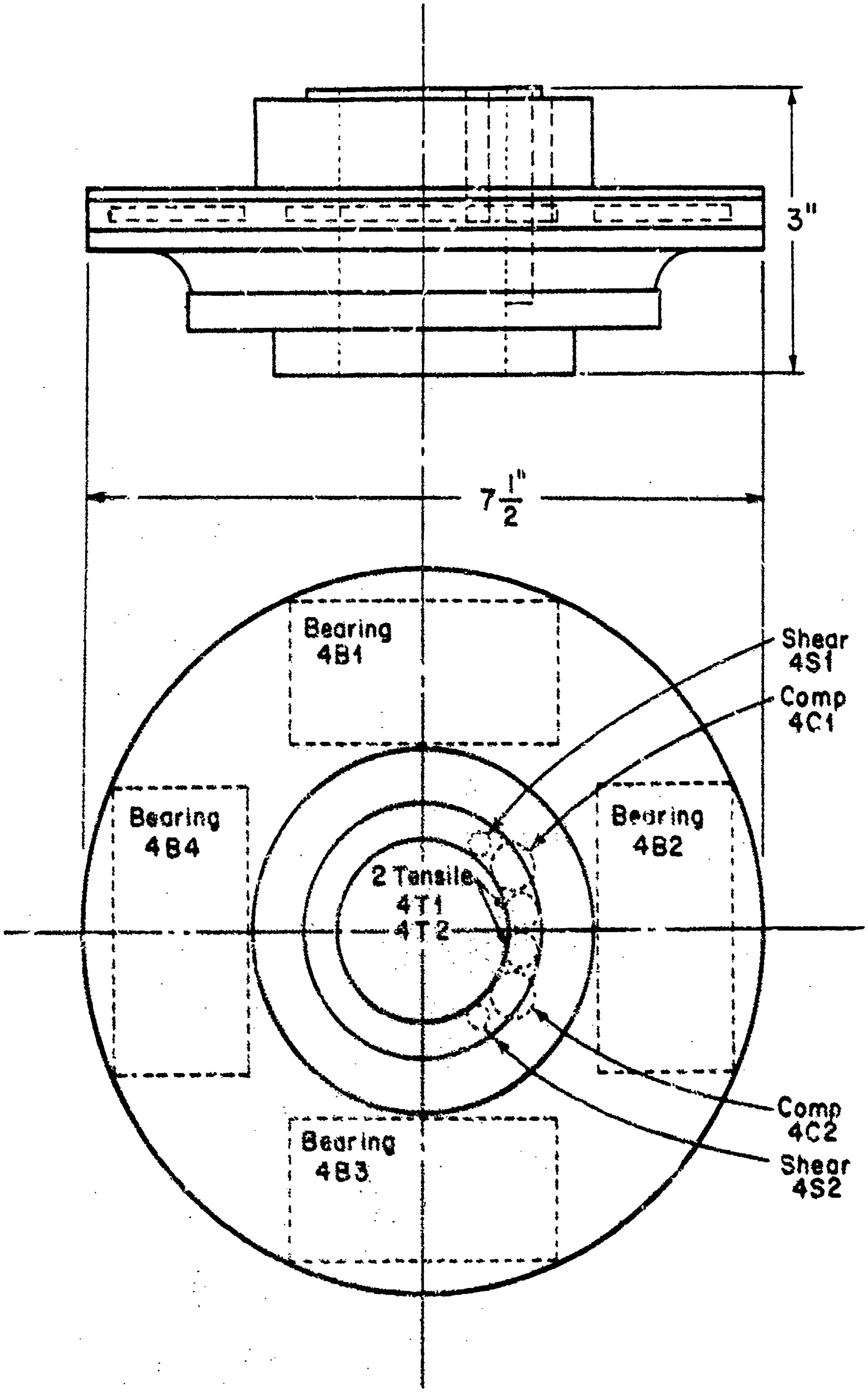


Figure 20. Location of test specimens for 15-5PH (H935) impeller #1 casting.

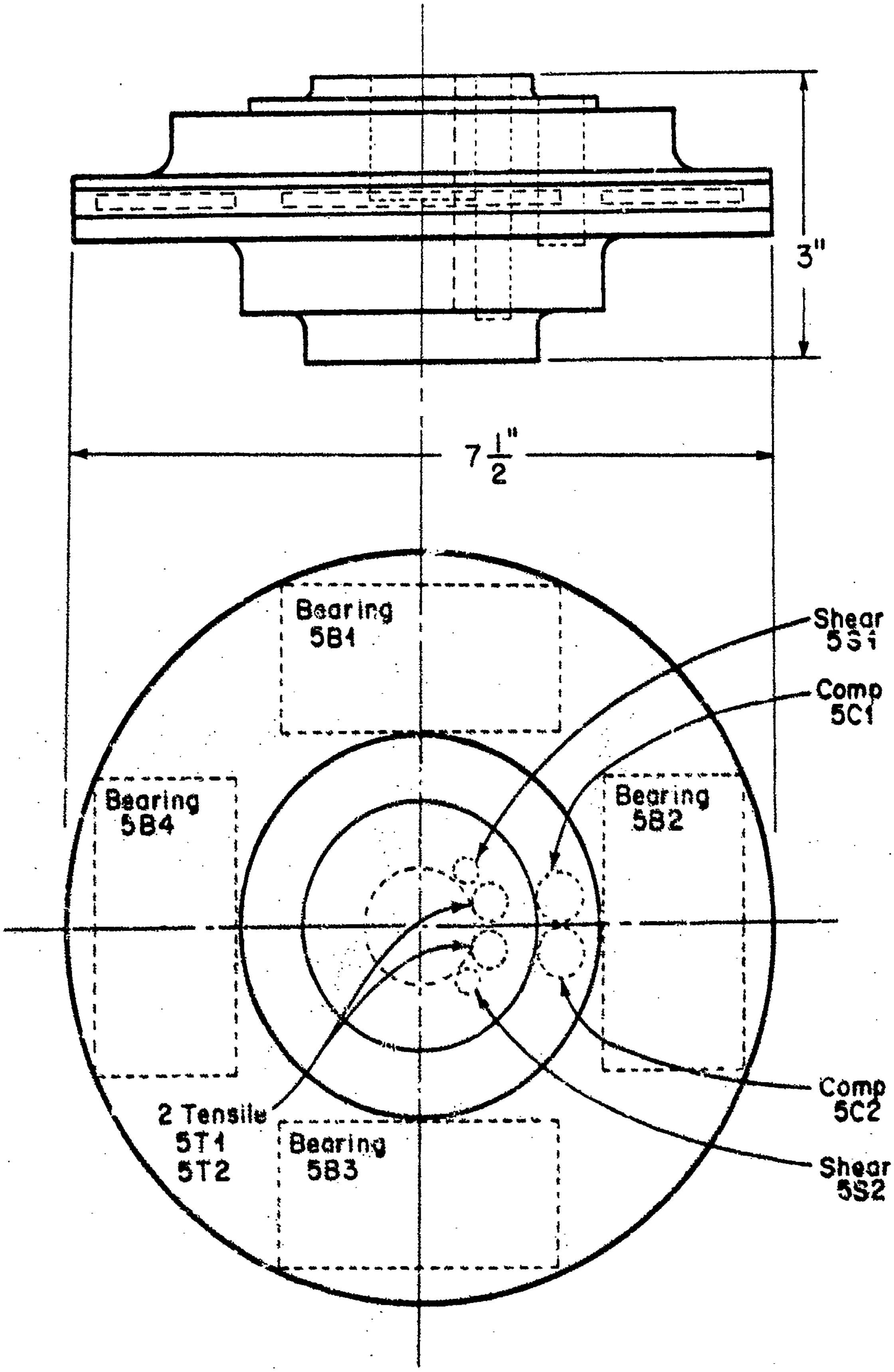


Figure 21. Location of test specimens for 15-5PH (H935) impeller #2 casting.

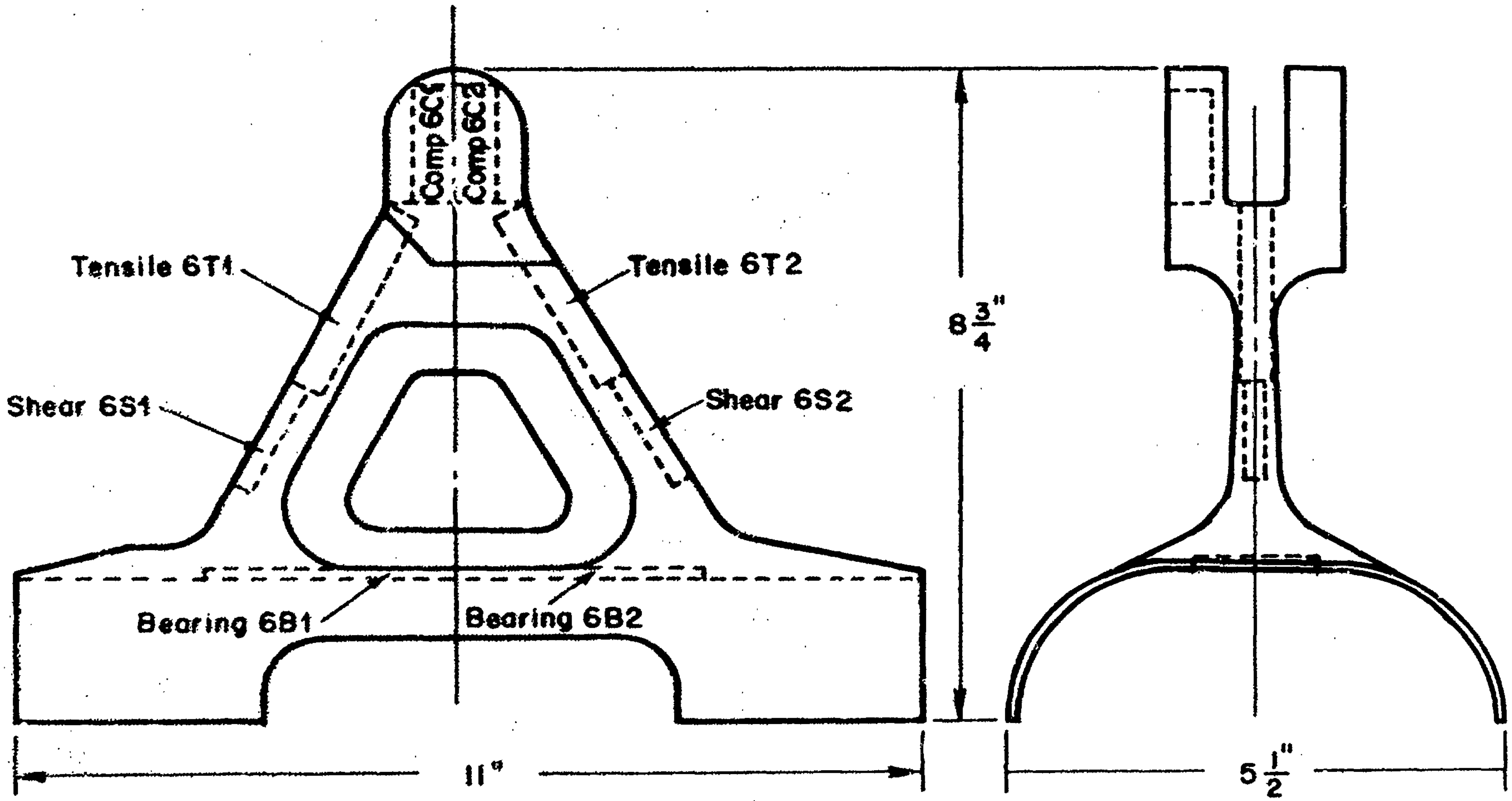


Figure 22. Test specimen location for 15-5PH (H935) A-bracket casting.

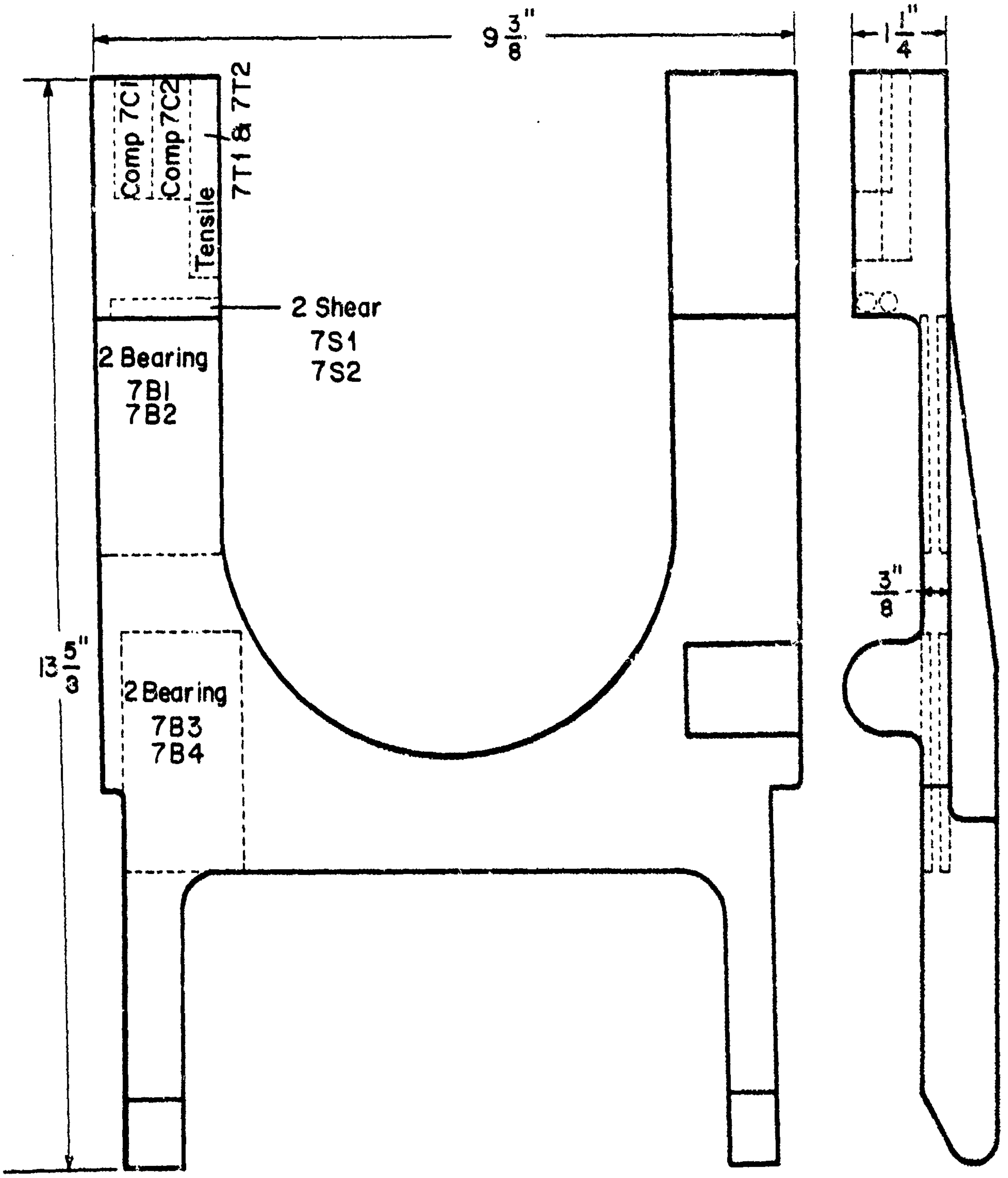
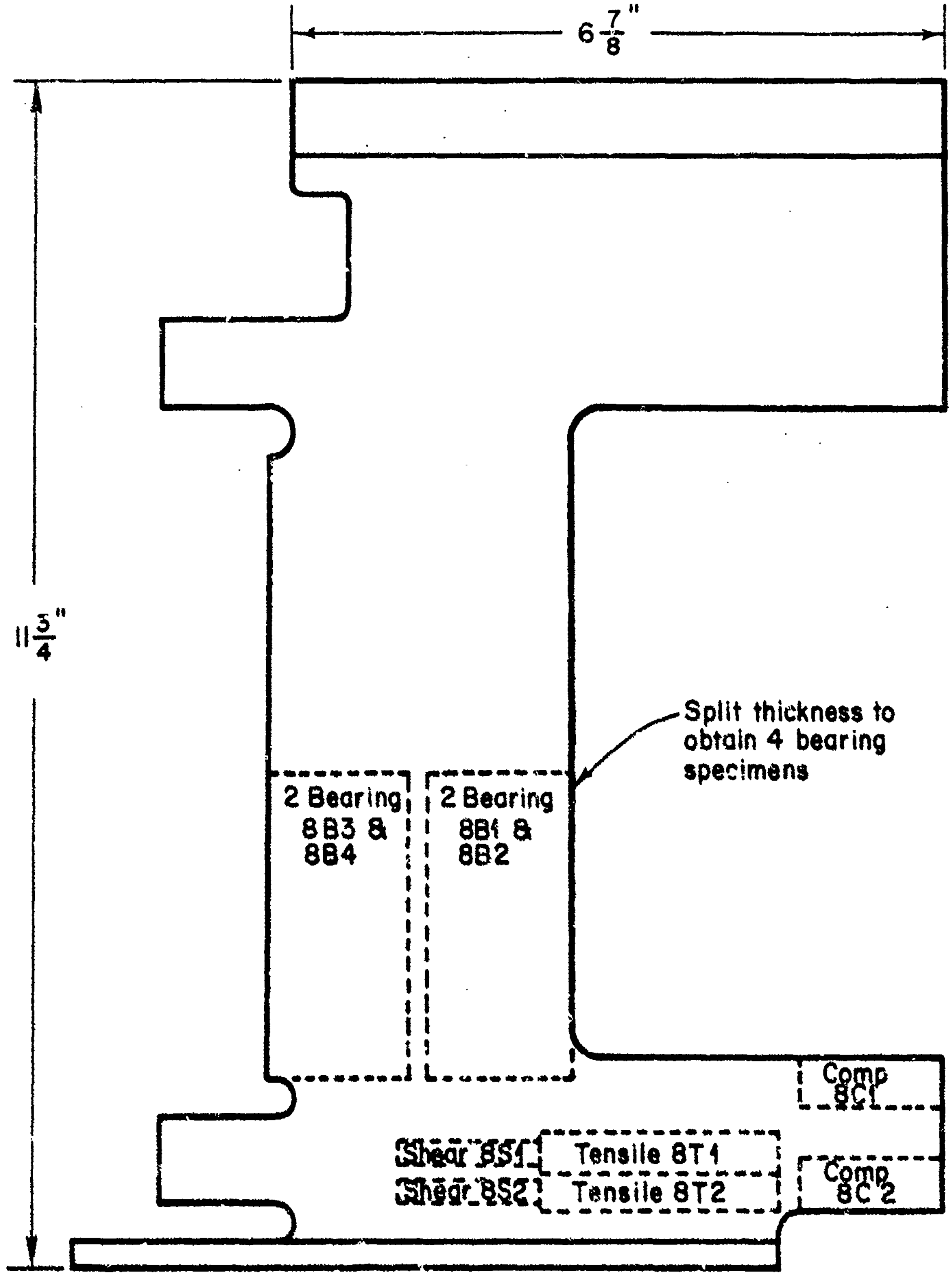


Figure 23. Test specimen location for 15-5PH (935) horseshoe bracket casting.



(Plan View)

Figure 24. Test specimen location for 15-5PH (H935) triangle bracket.

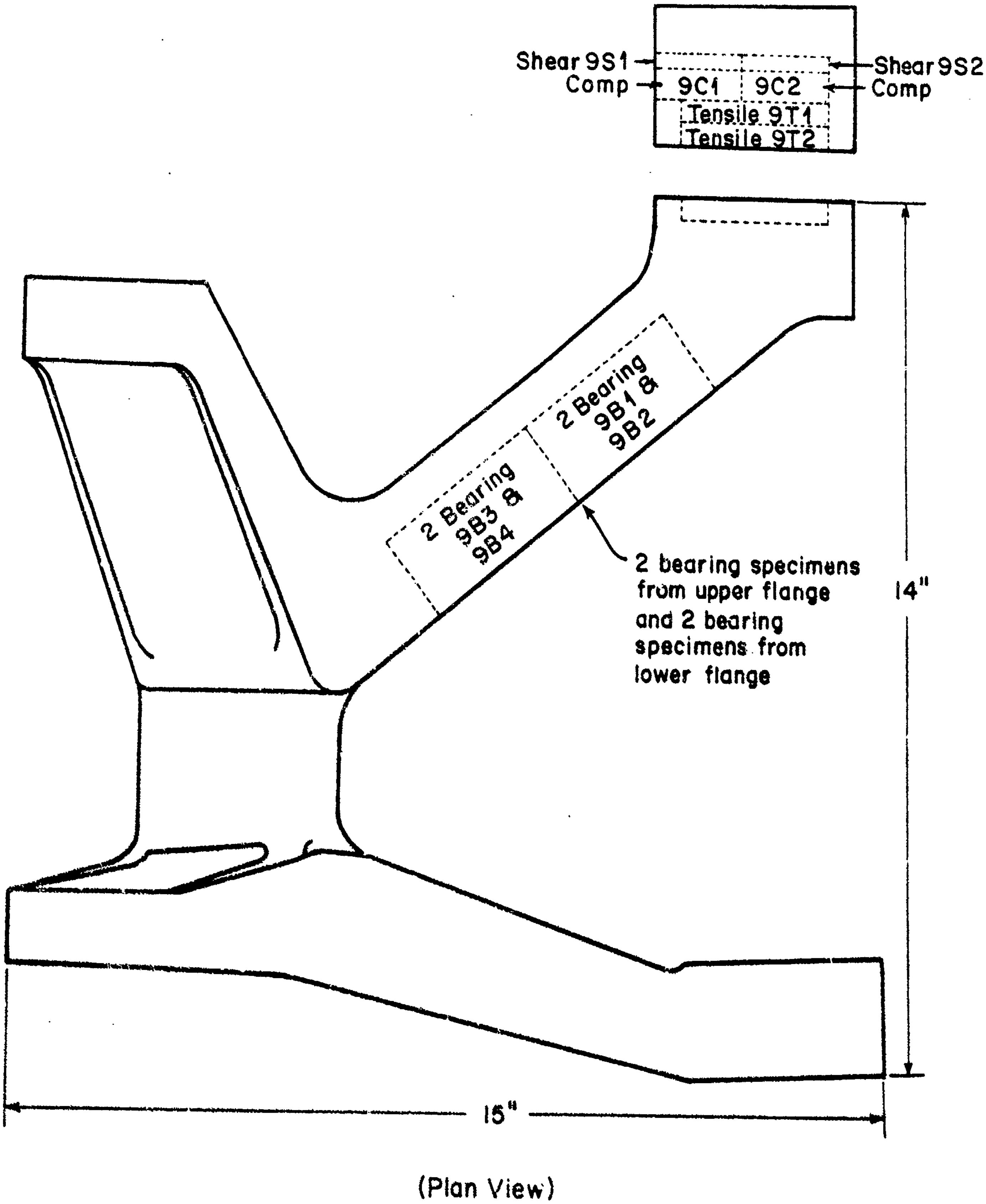


Figure 25. Test specimen location for 15-5PH (H935) bellcrank casting.

Element	Percent Min.	Percent Max.
Carbon	--	0.05
Manganese	--	0.60
Silicon	0.50	1.00
Phosphorus	--	0.025
Sulfur	--	0.025
Chromium	14.00	15.50
Nickel	4.20	5.00
Columbium + Tantalum	0.15	0.30
Copper	2.50	3.20
Nitrogen	--	0.05

The tensile properties of the castings conformed to AMS 5400.

Location of Test Specimens

The location of the various test specimens was dictated by the size and configuration of the casting. Duplicate rather than triplicate specimens were tested due to the size and configuration of the castings. Bearing specimens could not be obtained from three castings, shaft, valve body, and cylinder, due to the configuration of the castings. Only two bearing specimens could be excised from the A-bracket. Sketches of the castings showing the location of test specimens for each casting are contained in Figures 17 through 25. The following code system was used to identify test specimens:

X X X

Casting Name — Type of Specimen — Specimen No.

Specimen No.: 1, 2, 3, 4, etc.

Type of Specimen	
Tension	= T
Compression	= C
Shear	= S
Bearing	= B

Casting Name	
Shaft	= 1
Valve Body	= 2
Cylinder	= 3
Impeller #1	= 4
Impeller #2	= 5
A-Bracket	= 6
Horseshoe Bracket	= 7
Triangle Bracket	= 8
Bellcrank	= 9

Specimen Configuration

The configurations of the test specimens are shown in Appendix B. Subsize tensile, compression from valve body only, and bearing specimens were utilized due to the size and configurations of the castings.

Inspection

In order to determine internal quality, the test specimens were radiographed after machining. The specimens exhibited very good quality. The acceptable defects in the test specimens did not exceed the requirement for Grade B of MIL-A-21180.

Test Results

Tensile. The results of tensile tests are shown in Tables 7 and 7(SI). In addition to tensile yield and ultimate strengths, elongation and modulus of elasticity values are indicated. A typical tensile stress-strain curve is presented in Figure 26. The tensile stress-strain curve was constructed in the same manner as those for 7149-T73 hand forgings.

Compression. The results of compression tests are shown in Tables 7 and 7(SI). Compressive modulus of elasticity values are listed in addition to the compressive yield strengths. The averge compressive modulus of elasticity was 28,500,000 psi, compared to an average tensile modulus of elasticity of 30,400,000 psi. The compressive modulus for steels is normally higher than the tensile modulus. The modulus values were calculated from information taken from the load-deformation curves. It was necessary to use a different type extensometer for the compression tests than for the tensile tests. It is believed that this reversed relationship in modulus values is due to this testing variable rather than a characteristic of the material. A typical compressive stress-strain curve is shown in Figure 27.

Shear. The results of shear tests are shown in Tables 7 and 7(SI). The commonly used double-shear, "rivet-tool" shear test was used so that the resulting shear data would be comparable to existing shear data for other precipitation hardening, corrosion resistant steel castings.

Bearing. The results of bearing tests are presented in Tables 7 and 7(SI).

Fatigue. Fatigue tests were not conducted due to the limited size and configuration of the castings.

TABLE 7. MECHANICAL PROPERTIES OF 15-5PH (H935) CORROSION RESISTANT STEEL CASTINGS

Casting Name	Approx. Thickness at Specimen Location, Inches	Specimen No.	Tensile: Ultimate Strength, ksi	Tensile: Yield Strength, ksi	Tensile: Elongation, percent	Tensile: Modulus, 10^3 ksi	Compressive: Yield Strength, ksi	Compressive: Modulus, 10^3 ksi	Ultimate Shear Strength ksi	Bearing e/D = 1.5: Ultimate Strength, ksi	Bearing e/D = 1.5: Yield Strength, ksi	Bearing e/D = 2.0: Ultimate Strength, ksi	Bearing e/D = 2.0: Yield Strength, ksi
Shaft	5/8	1	181.0	172.5	13.0	31.3	182.0	28.4	123.7	-	-	-	-
		2	-	-	-	-	180.2	28.2	122.7	-	-	-	-
		Avg.	181.0	172.5	13.0	31.3	181.1	28.3	123.2				
Valve Body	1/2	1	191.7	173.6	12.0	30.4	180.9	28.3	124.2	-	-	-	-
		2	192.0	172.8	12.0	30.9	185.3	29.8	124.2	-	-	-	-
		Avg.	191.8	173.2	12.0	30.9	185.3	29.8	124.2				
Cylinder	1/2	1	178.6	169.1	9.0	29.3	175.9	29.1	114.8	-	-	-	-
		2	181.2	170.0	12.0	32.5	176.9	28.7	115.1				
		Avg.	179.9	169.6	10.5	30.9	176.4	28.9	115.0				
Impeller #1	1	1	189.5	174.3	12.0	31.3	183.8	28.6	121.9	299.5	247.9	393.1	307.3
		2	190.0	176.4	12.0	29.4	184.6	28.1	122.7	309.9	259.9	402.5	292.1
		Avg.	189.8	175.4	12.0	30.4	184.2	28.4	122.3	304.7	253.9	397.8	299.7
Impeller #2	1-5/8	1	178.4	168.2	6.0	31.4	176.2	28.2	114.3	284.7	235.1	369.8	267.3
		2	177.8	168.7	8.0	29.4	172.5	28.3	113.4	280.2	232.7	369.8	264.8
		Avg.	178.1	168.4	7.0	30.4	174.4	28.2	113.8	282.4	233.9	369.8	266.0
π-Bracket	3/4	1	181.6	173.4	14.0	30.3	178.2	28.1	115.3	299.5	241.1	386.0	279.7
		2	192.2	175.7	15.0	30.4	176.9	28.3	115.3	-	-	-	-
		Avg.	186.9	174.6	14.5	30.4	177.6	28.2	115.3	299.5	241.1	386.0	279.7
Horseshoe Bracket	1 1/4	1	192.0	175.8	14.0	28.1	183.0	28.1	124.5	315.8	261.4	390.6	289.1
		2	182.4	174.3	14.0	29.1	182.0	28.3	124.0	316.5	251.3	377.7	288.1
		Avg.	187.2	175.0	14.0	28.9	182.5	28.2	124.2	316.2	256.4	384.2	288.6
Triangle Bracket	1/2	1	191.0	176.4	7.0	29.7	183.3	28.6	124.0	303.5	250.3	406.0	290.0
		2	191.3	175.7	8.0	30.8	181.8	28.2	123.2	312.8	257.8	401.0	291.1
		Avg.	191.2	176.0	7.5	30.2	182.6	28.4	123.6	308.2	254.0	403.5	290.6
Bellcrank	1 7/8	1	193.2	175.5	9.0	29.7	179.2	28.9	116.3	295.6	249.0	384.7	282.2
		2	180.2	173.6	6.0	30.6	179.0	28.1	114.9	296.1	242.8	381.7	285.1
		Avg.	186.7	174.6	7.5	30.2	179.1	28.5	115.6	295.8	245.9	383.2	283.6

(1) Specimen numbers for e/D = 2.0 were 3 and 4.

TABLE 7 (SI). MECHANICAL PROPERTIES OF 15-5PH (H935) CORROSION RESISTANT STEEL CASTINGS

Casting Name	Approx. Thickness at Specimen Location mm	Speci-men No.	Tensile Ultimate Strength, MPa	Tensile Yield Strength, MPa	Tensile Elong-ation, percent	Tensile Modulus GPa	Compressive Yield Strength, MPa	Compressive Modulus GPa	Ultimate Shear Strength, MPa	Bearing e/D = 1.5 Ultimate Strength, MPa	Bearing e/D = 1.5 Yield Strength, MPa	Bearing e/D = 2.0(1) Ultimate Strength, MPa	Bearing e/D = 2.0(1) Yield Strength, MPa
Shaft	15.9	1	1248.0	1189.4	13.0	215.8	1254.9	195.8	852.0	-	-	-	-
		2	-	-	-	-	1242.5	194.4	846.0	-	-	-	-
		Avg.	1248.0	1189.4	13.0	215.8	1248.7	195.1	849.4	-	-	-	-
Valve Body	12.7	1	1321.8	1197.0	12.0	209.6	1247.3	195.1	856.4	-	-	-	-
		2	1323.8	1191.4	12.0	213.0	1277.6	205.5	856.4	-	-	-	-
		Avg.	1322.8	1194.2	12.0	211.3	1262.3	200.3	856.4	-	-	-	-
Cylinder	12.7	1	1231.4	1165.9	9.0	202.0	1212.8	200.6	791.5	-	-	-	-
		2	1249.4	1172.2	12.0	224.1	1219.7	197.9	793.6	-	-	-	-
		Avg.	1240.4	1169.0	10.5	213.0	1216.2	199.2	792.6	-	-	-	-
Impeller #1	25.4	1	1306.6	1201.8	12.0	215.8	1267.3	197.2	840.5	2065.0	1709.3	2710.4	2118.8
		2	1310.0	1216.3	12.0	202.7	1272.8	193.7	846.0	2136.8	1792.0	2775.2	2014.0
		Avg.	1308.3	1209.0	12.0	209.2	1270.0	195.5	843.2	2100.9	1750.6	2742.8	2066.4
Impeller #2	41.3	1	1230.0	1159.7	6.0	216.5	1214.9	194.4	788.1	1963.0	1621.0	2549.8	1843.0
		2	1225.9	1163.2	8.0	202.7	1189.4	195.1	781.9	1932.0	1604.5	2549.8	1825.8
		Avg.	1228.0	1161.4	7.0	209.6	1202.2	194.8	785.0	1947.5	1612.8	2549.8	1834.4
A-Bracket	19.0	1	1252.1	1195.6	14.0	208.9	1228.7	193.7	795.0	2065.0	1662.4	2661.5	1928.5
		2	1325.2	1211.4	15.0	209.6	1219.7	195.1	795.0	-	-	-	-
		Avg.	1288.6	1203.5	14.5	209.3	1224.2	194.4	795.0	2065.0	1662.4	2661.5	1928.5
Horseshoe	31.7	1	1323.8	1212.1	14.0	193.7	1261.8	193.7	858.4	2177.4	1802.4	2693.2	1993.3
		2	1257.6	1201.8	14.0	204.8	1254.9	195.1	885.0	2182.3	1732.7	2604.2	1986.4
		Avg.	1290.7	1207.0	14.0	199.2	1258.4	194.4	856.7	2179.9	1767.6	2648.7	1989.9
Triangle Bracket	12.7	1	1316.9	1216.3	7.0	204.8	1263.8	197.2	855.0	2092.6	1725.8	2799.4	1999.6
		2	1319.0	1211.4	8.0	212.4	1253.5	194.4	849.5	2156.8	1777.5	2764.9	2007.1
		Avg.	1318.0	1213.8	7.5	208.6	1258.6	195.8	852.2	2124.7	1751.6	2782.1	2003.4
Bellcrank	47.6	1	1332.1	1210.1	9.0	204.8	1235.6	199.3	801.9	2038.2	1716.8	2652.5	1945.8
		2	1242.5	1197.0	6.0	211.0	1234.2	193.7	792.2	2041.6	1674.1	2631.8	1965.8
		Avg.	1287.3	1203.6	7.5	207.9	1234.9	196.5	797.0	2039.9	1695.4	2642.2	1955.8

(1) Specimen numbers for e/D = 2.0 were 3 and 4.

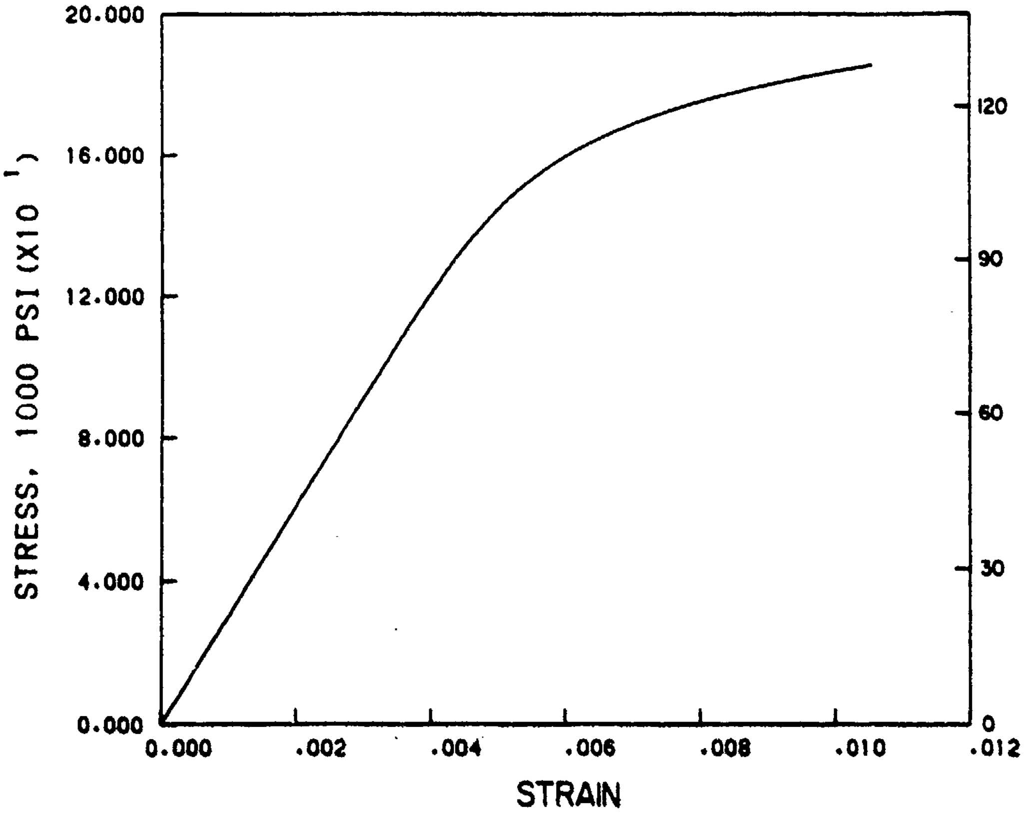


Figure 26. Typical tensile stress-strain curve for 15-5PH (H935) corrosion resistant steel castings.

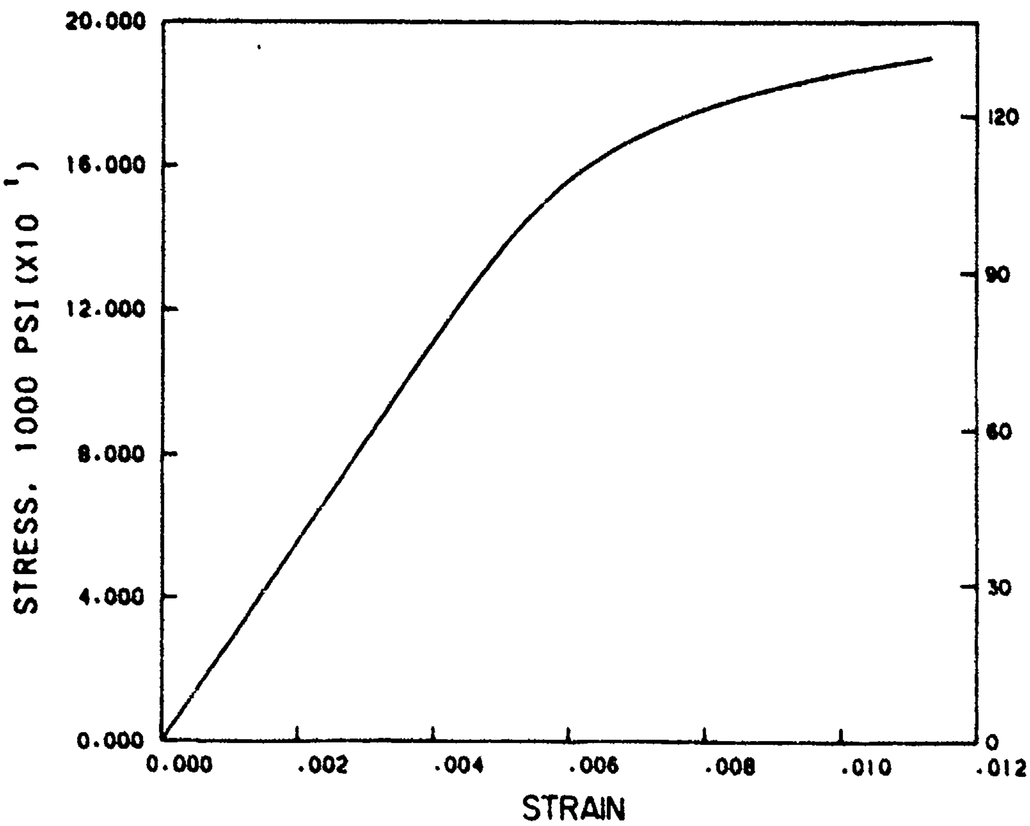


Figure 27. Typical compressive stress-strain curve for 15-5PH (H935) corrosion resistant steel castings.

Inconel 718 Sheet (Solution Treated and Aged)

Background

Because of its many attractive characteristics, Inconel 718 is being used for applications other than for parts exposed to high temperatures. Therefore, data for mechanical properties other than those critical for high temperature performance are needed. Inconel 718 is currently contained in MIL-HDBK-5, but design values for properties other than tensile yield and ultimate strengths are missing. Consequently, it was desirable to determine the mechanical properties of Inconel 718 sheet in the solution treated and aged condition so that design values can be subsequently determined.

Material

The Air Force supplied eight heats of Inconel 718 sheet in the solution treated condition. The material had been produced to AMS 5596 by Inco Alloys International (formerly Huntington Alloys). The chemical composition, as determined by Inco Alloys, is shown below:

	Percent							
Element	65S2EK	77J7EK	17K0EK	12K1EK	68J7EK	67J6EK	70JEEK	77J9EK
Carbon	0.04	0.03	0.04	0.04	0.04	0.04	0.06	0.04
Manganese	0.14	0.13	0.12	0.13	0.14	0.13	0.13	0.12
Iron	18.01	17.24	18.05	17.03	17.84	18.10	18.92	17.77
Sulfur	0.001	0.001	0.002	0.001	0.001	0.002	0.002	0.001
Silicon	0.28	0.25	0.13	0.15	0.24	0.21	0.25	0.25
Copper	0.25	0.10	0.20	0.23	0.16	0.15	0.17	0.20
Nickel	53.16	54.04	54.28	54.50	53.36	53.20	52.42	53.62
Chromium	18.28	18.14	17.63	17.39	18.29	18.18	18.28	18.30
Aluminum	0.48	0.54	0.51	0.58	0.51	0.56	0.55	0.42
Titanium	0.83	0.92	0.93	0.93	0.97	0.95	0.91	0.89
Cobalt	0.18	0.13	0.12	0.10	0.21	0.11	0.14	0.12
Molybdenum	3.05	3.27	3.03	3.05	3.04	3.12	2.95	3.09
Columbium + Tantalum	5.30	5.13	4.96	5.07	5.20	5.25	5.22	5.18
Phosphorus	0.013	0.011	0.013	0.013	0.013	0.014	0.012	0.011
Boron	0.002	0.003	0.003	0.002	0.002	0.002	0.002	0.002

The chemical composition and tensile properties conformed to AMS 5596.

The size of the sheet received for testing and the heat number are shown below:

Nominal Thickness, inches	Width, inches	(Long. Grain Dir.) Length, inches	Heat Number
0.016	36	24	65J2EK
0.045	36	23	77J7EK
0.050	36	24	17K0EK
0.080	36	24	12K1EK
0.109	36	24	68J7EK
0.125	36	23	67J6EK
0.187	36	24	70J3EK
0.250	11	11 (3 pcs)	77J9EK

The material was supplied in the 1750 F (1725-1825 F) solution treated condition. After machining the test specimens were precipitation heat treated in a vacuum furnace according to AMS 5596 as follows: Heat to 1325 $\pm$ 15 F and hold for 8 $\pm$ 0.5 hours, cool at 100 $\pm$ 15 degrees per hour to 1150 $\pm$ 15 F for 8 $\pm$ 0.5 hours, and cool in air to room temperature. This heat treat is used primarily for parts requiring maximum resistance to creep and stress rupture.

Location of Test Specimens

The location of test specimens is shown in Figures 28 through 31. The following code system was used to identify test specimens:

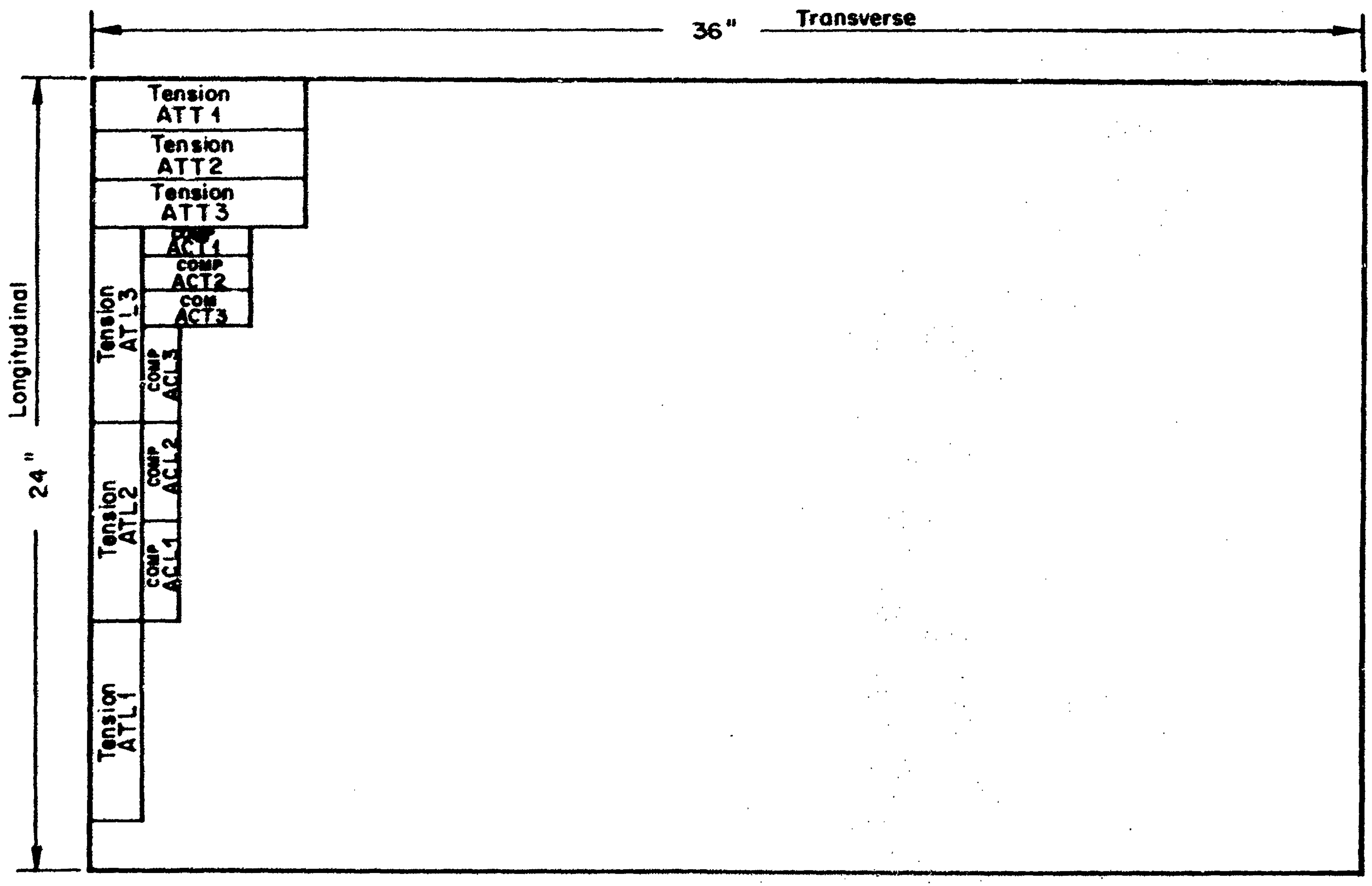


Figure 28. Location of test specimens for Inconel 718 sheet--0.016 inch thick.

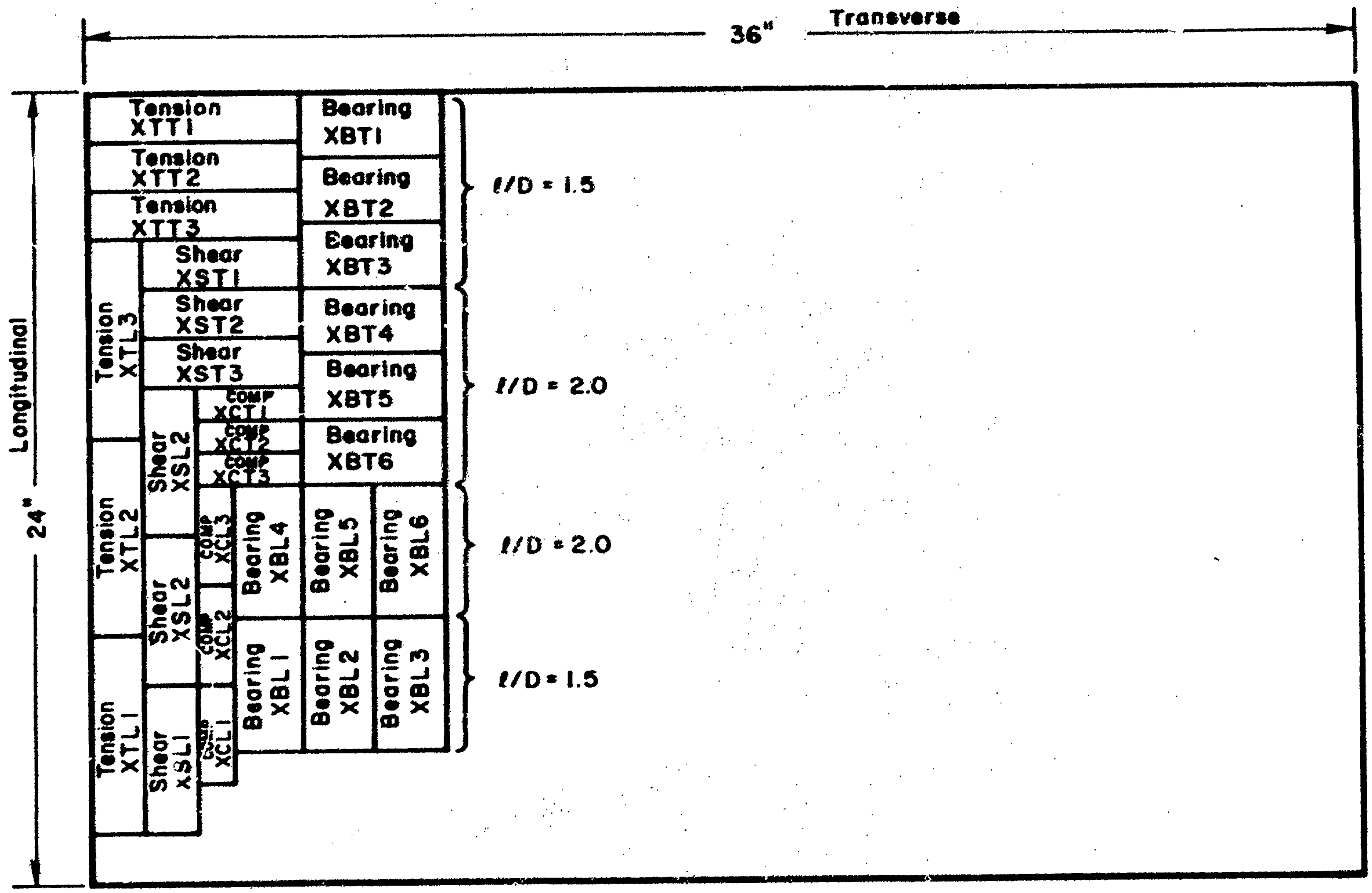


Figure 29. Location of test specimens for Inconel 718 sheet--0.045, 0.050, 0.080, 0.125, and 0.187 inches thick.

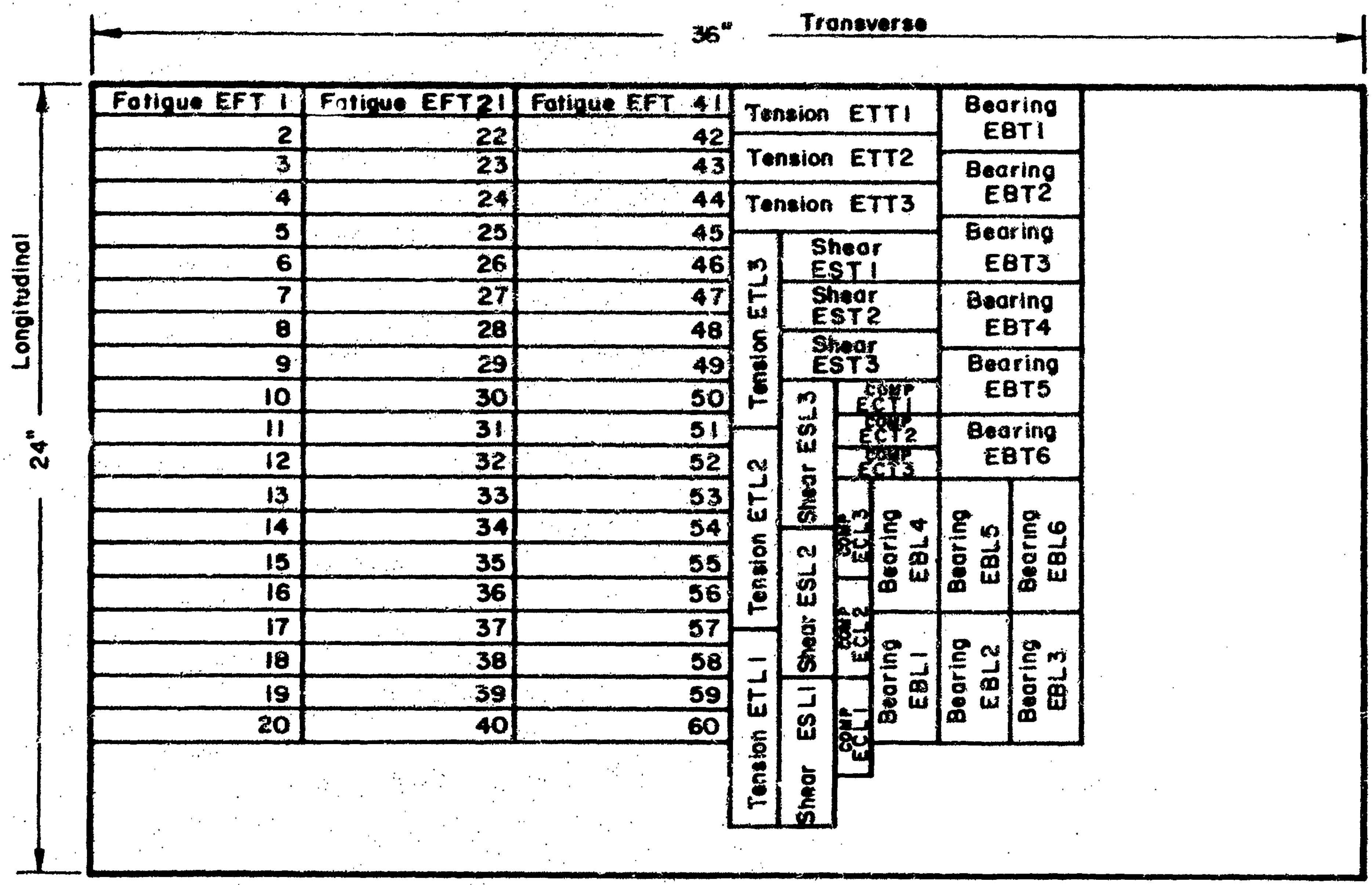
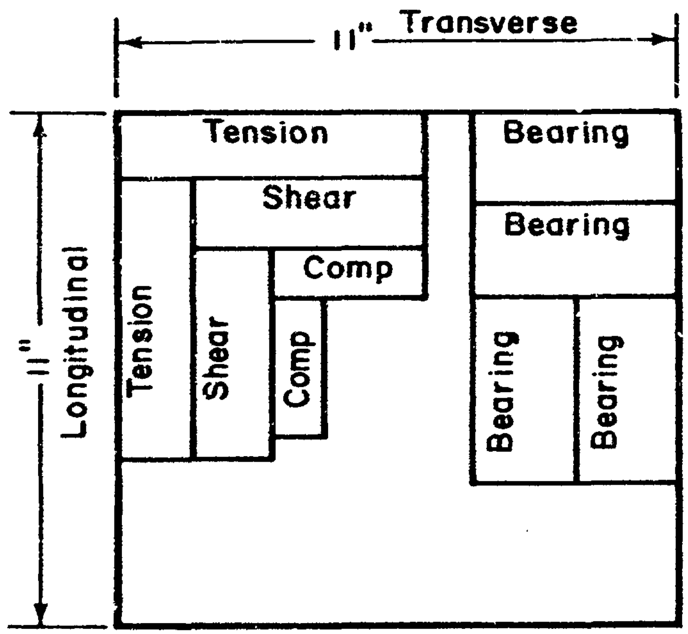


Figure 30. Location of test specimens for Inconel 718 sheet--0.109 inch thick.



Note: Specimens removed from 3 pieces

Figure 31. Typical location of test specimens for Inconel 718 sheet (three pieces)--0.250 inch thick.

X X X X

Lot Number — Type of Specimen — Grain Direction — Specimen No.

Specimen No.: 1, 2, 3, 4, etc.

Grain Direction:
Longitudinal = L
Long Transverse = T

Type of Specimen:
Tension = T   Bearing = B
Compression = C   Fatigue = F
Shear = S

Lot Number:

0.016"	65J2EK	= A
0.045"	77J7EK	= B
0.050"	17K0EK	= C
0.080"	12K1EK	= D
0.109"	68J7EK	= E
0.125"	67J6EK	= F
0.187"	70J3EK	= G
0.250"	77J9EK	= H

Specimen Configuration

The configurations of the test specimens are shown in Appendix B. Bearing specimens from the 0.125-, 0.187-, and 0.250-inch sheet were machined to 0.100-inch thickness by removing an equal amount of material from each surface.

Test Results

Tensile. The results of the tensile tests are shown in Tables 8 and 8(SI). In addition to tensile yield and ultimate strengths, elongation and modulus of elasticity values are indicated. Typical tensile stress-strain

TABLE 8. MECHANICAL PROPERTIES OF INCONEL 718 SOLUTION TREATED AND AGED SHEET

Thickness, inches	Grain Direction	Speci-men No.	Tensile				Compressive		Ultimate Shear Strength, ksi	Bearing			
										e/D = 1.5		e/D = 2.0(1)	
			Ultimate Strength, ksi	Yield Strength, ksi	Elong-ation, percent	Modulus, 10^3 ksi	Yield Strength, ksi	Modulus 10^3 ksi		Ultimate Strength, ksi	Yield Strength, ksi	Ultimate Strength, ksi	Yield Strength, ksi
0.016	L	1	209.5	179.3	19.0	29.0	(2)	30.6	-	-	-	-	-
		2	209.7	179.2	19.5	29.2	(2)	31.9	-	-	-	-	-
		3	207.8	177.2	19.0	28.9	(2)	30.6	-	-	-	-	-
		Avg.	209.0	178.6	19.2	29.0		31.0	-	-	-	-	-
	LT	1	205.9	179.6	20.0	30.4	(2)	32.4	-	-	-	-	-
		2	206.1	179.2	19.0	29.5	(2)	32.4	-	-	-	-	-
		3	204.4	179.6	14.5(3)	29.8	(2)	32.3	-	-	-	-	-
		Avg.	205.5	179.5	19.5	29.9		32.4	-	-	-	-	-
0.045	L	1	204.6	177.3	20.5	29.6	192.4	31.0	149.6	(5)	(5)	(5)	(5)
		2	206.7	178.5	20.0	29.5	193.3	31.0	146.7	(5)	(5)	(5)	(5)
		3	206.0	178.2	21.0	29.4	193.4	31.1	139.4	(5)	(5)	(5)	(5)
		Avg.	205.8	178.0	20.5	29.5	193.0	31.0	145.2				
	LT	1	201.7	177.0	22.0	29.8	195.5	31.3	152.5	(5)	(5)	(5)	(5)
		2	202.7	178.3	21.0	30.2	196.6	31.4	149.1	(5)	(5)	(5)	(5)
		3	203.4	179.5	21.5	30.3	197.1	31.3	154.0	(5)	(5)	(5)	(5)
		Avg.	202.6	178.3	21.5	30.1	196.4	31.3	151.9				
0.050	L	1	206.6	176.5	21.5	30.2	189.8	30.5	150.4	(5)	(5)	(5)	(5)
		2	207.1	177.4	20.5	30.1	190.6	30.9	156.1	(5)	(5)	(5)	(5)
		3	205.9	176.2	21.0	29.9	190.1	30.7	150.0	(5)	(5)	(5)	(5)
		Avg.	206.5	176.7	21.0	30.1	190.2	30.7	152.2				
	LT	1	201.5	175.1	21.0	31.1	193.5	31.6	149.0	(5)	(5)	(5)	(5)
		2	201.8	176.1	21.0	30.7	194.0	32.3	147.4	(5)	(5)	(5)	(5)
		3	202.1	177.0	20.0	30.5	193.7	31.6	149.3	(5)	(5)	(5)	(5)
		Avg.	201.8	176.1	20.7	30.8	193.7	31.8	148.6				

TABLE 8. MECHANICAL PROPERTIES OF INCONEL 718 SOLUTION TREATED AND AGED SHEET (Continued)

Thickness, inches	Grain Direction	Specimen No.	Tensile Ultimate Strength, ksi	Tensile Yield Strength, ksi	Tensile Elongation, percent	Tensile Modulus, 10^3 ksi	Compressive Yield Strength, ksi	Compressive Modulus 10^3 ksi	Ultimate Shear Strength, ksi	Bearing e/D = 1.5 Ultimate Strength, ksi	Bearing e/D = 1.5 Yield Strength, ksi	Bearing e/D = 2.0(1) Ultimate Strength, ksi	Bearing e/D = 2.0(1) Yield Strength, ksi
0.080	L	1	200.6	172.2	21.5	29.8	183.4	30.9	153.3	310.6	229.2	441.8	289.9
		2	200.5	172.0	21.0	29.6	183.7	30.6	150.4	337.3	252.2	439.6	288.0
		3	197.5	172.0	21.5	29.9	183.0	30.9	146.1	332.2	255.9	444.0	284.3
		Avg.	199.5	172.1	21.3	29.8	183.4	30.8	149.9	326.7	245.8	441.8	287.4
	LT	1	197.7	171.1	21.0	30.8	184.8	30.6	150.9	329.3	249.3	436.1	284.1
		2	197.4	171.9	21.5	30.9	184.8	31.3	141.4	333.7	248.7	438.1	284.1
		3	201.3	172.2	20.0	29.8	184.6	31.2	150.1	333.7	244.3	440.6	289.5
		Avg.	198.8	171.7	20.8	30.5	184.7	31.0	147.5	332.2	247.4	438.3	286.1
0.109	L	1	211.8	183.3	18.5	29.6	196.8	30.3	140.8	339.6	251.5	447.8	311.3
		2	211.4	183.7	-	29.8	194.5	29.6	132.3	345.6	256.5	436.2	311.1
		3	211.4	183.1	19.0	30.2	195.5	32.0	137.4	333.0	266.1	434.8	305.3
		Avg.	211.5	183.4	18.8	29.9	195.6	30.6	136.8	339.4	258.0	439.6	309.2
	LT	1	208.7	184.5	18.0	30.7	198.1	32.1	143.2	337.0	265.1	443.9	306.5
		2	208.5	183.9	19.0	30.6	198.1	34.2	144.2	337.9	260.8	429.9	292.2
		3	208.8	184.1	18.0	30.9	198.2	32.7	145.0	336.2	263.4	428.4	295.1
		Avg.	208.7	184.2	18.3	30.7	198.1	33.0	144.1	337.0	263.1	434.1	297.9
0.125	L	1	203.5	175.4	21.0	29.1	190.5	31.7	136.3	336.0	255.2	439.9	297.7
		2	202.9	174.9	21.0	29.8	(4)	(4)	136.6	325.0	258.2	438.5	291.2
		3	202.0	174.6	20.5	29.4	192.8	32.0	139.5	335.6	263.9	431.6	298.8
		Avg.	203.1	175.0	20.8	29.4	191.6	31.8	137.5	332.2	259.1	436.7	295.9
	LT	1	201.1	174.6	20.5	30.4	192.0	31.9	141.9	328.7	268.9	440.1	296.5
		2	201.0	174.9	20.0	30.1	191.3	31.7	137.2	332.8	253.8	437.3	299.1
		3	201.2	175.7	20.0	30.2	191.9	31.2	146.6	334.3	257.1	439.6	299.5
		Avg.	201.1	175.1	20.2	30.2	191.7	31.6	141.9	331.9	257.1	439.0	298.4

TABLE 8. MECHANICAL PROPERTIES OF INCONEL 718 SOLUTION TREATED AND AGED SHEET (Concluded)

Thickness, inches	Grain Direction	Specimen No.	Tensile				Compressive		Ultimate Shear Strength, ksi	Bearing			
										e/D = 1.5		e/D = 2.0(1)	
			Ultimate Strength, ksi	Yield Strength, ksi	Elongation, percent	Modulus, 10^3 ksi	Yield Strength, ksi	Modulus 10^3 ksi		Ultimate Strength, ksi	Yield Strength, ksi	Ultimate Strength, ksi	Yield Strength, ksi
0.187	L	1	201.7	172.5	20.0	28.9	184.2	30.4	142.4	332.6	254.1	418.6	292.9
		2	201.5	171.7	22.0	28.9	184.2	30.7	144.5	336.1	249.0	429.9	295.7
		3	201.4	172.2	20.0	29.2	184.3	30.2	146.8	330.4	249.0	431.8	294.4
		Avg.	201.5	172.1	20.7	29.0	184.2	30.4	144.6	333.0	250.7	426.8	294.3
	LT	1	201.1	173.8	20.5	29.6	187.5	31.4	142.2	336.5	254.7	425.0	297.3
		2	200.8	173.8	20.5	29.7	188.3	32.6	149.3	319.6	261.1	427.8	298.3
		3	200.9	174.2	21.0	29.1	188.2	31.4	147.7	316.4	254.0	435.6	301.0
		Avg.	200.9	173.9	20.7	29.5	188.0	31.8	146.4	324.2	256.0	429.5	298.9
0.250	L	1	199.4	172.5	21.0	28.6	183.0	31.3	148.9	333.9	257.8	407.7	274.0
		2	198.0	171.4	21.5	29.0	183.1	31.6	152.6	331.3	251.5	435.8	297.0
		3	198.2	170.6	22.0	28.6	183.3	31.4	148.2	334.5	253.7	439.1	294.0
		Avg.	198.5	171.5	21.5	28.7	183.1	31.4	149.9	333.2	254.3	427.5	288.3
	LT	1	198.9	175.5	20.0	30.6	187.9	31.8	149.1	333.7	257.5	435.0	293.5
		2	199.7	174.8	19.5	29.3	187.9	32.6	150.4	337.1	260.2	441.4	309.4
		3	199.2	175.4	20.0	29.8	187.6	31.9	151.8	334.0	257.5	437.5	322.5
		Avg.	199.3	175.2	19.8	29.9	187.8	32.1	150.4	334.9	258.4	438.0	308.5

(1) Specimen numbers for e/D = 2.0 were 4 through 6.
(2) Specimen buckled before yield strength.
(3) Specimen failed in surface flaw--not included in average.
(4) Load deformation curve erratic.
(5) Excessive bending of specimen.

TABLE 8 (SI). MECHANICAL PROPERTIES OF INCONEL 718 SOLUTION TREATED AND AGED SHEET

Thickness, mm	Grain Direction	Specimen No.	Tensile Ultimate Strength, MPa	Tensile Yield Strength, MPa	Tensile Elongation, Percent	Tensile Modulus, GPa	Compressive Yield Strength, MPa	Compressive Modulus, GPa	Ultimate Shear Strength, MPa	Bearing e/D = 1.5 Ultimate Strength, MPa	Bearing e/D = 1.5 Yield Strength, MPa	Bearing e/D = 2.0(1) Ultimate Strength, MPa	Bearing e/D = 2.0(1) Yield Strength, MPa
0.4	L	1	1444.5	1236.3	19.0	200.0	(2)	211.0	-	-	-	-	-
		2	1445.9	1235.6	19.5	201.3	(2)	220.0	-	-	-	-	-
		3	1432.8	1221.8	10.0	199.3	(2)	211.0	-	-	-	-	-
		Avg.	1441.1	1231.2	19.2	200.2		214.0					
	LT	1	1419.7	1238.3	20.0	209.6	(2)	223.4	-	-	-	-	-
		2	1421.0	1235.6	19.0	203.4	(2)	223.4	-	-	-	-	-
		3	1409.3	1238.3	14.5(3)	205.5	(2)	222.7	-	-	-	-	-
		Avg.	1416.6	1237.4	19.5	206.2		223.2					
1.1	L	1	1410.7	1222.5	20.5	204.1	1326.6	213.7	1031.5	(5)	(5)	(5)	(5)
		2	1425.2	1230.8	20.0	203.4	1332.8	213.7	1011.5	(5)	(5)	(5)	(5)
		3	1420.4	1228.7	21.0	202.7	1333.5	214.4	961.2	(5)	(5)	(5)	(5)
		Avg.	1418.8	1227.3	20.5	203.4	1331.0	213.9	1001.4				
	LT	1	1390.7	1220.4	22.0	205.5	1348.0	215.8	1051.5	(5)	(5)	(5)	(5)
		2	1397.6	1229.4	21.0	208.2	1355.6	216.5	1028.0	(5)	(5)	(5)	(5)
		3	1402.4	1237.6	21.5	208.9	1359.0	215.8	1061.8	(5)	(5)	(5)	(5)
		Avg.	1396.9	1229.1	21.5	207.5	1354.2	216.0	1047.1				
1.3	L	1	1424.5	1217.0	21.5	208.2	1308.7	210.3	1037.0	(5)	(5)	(5)	(5)
		2	1428.0	1223.2	20.5	207.5	1314.2	213.0	1076.3	(5)	(5)	(5)	(5)
		3	1419.7	1214.9	21.0	206.2	1310.7	211.7	1034.2	(5)	(5)	(5)	(5)
		Avg.	1424.1	1218.4	21.0	207.3	1311.2	211.7	1049.2				
	LT	1	1389.3	1207.3	21.0	214.4	1334.2	217.9	1027.4	(5)	(5)	(5)	(5)
		2	1391.4	1214.2	21.0	211.7	1337.6	222.7	1016.3	(5)	(5)	(5)	(5)
		3	1393.5	1220.4	20.0	210.3	1335.6	217.9	1029.4	(5)	(5)	(5)	(5)
		Avg.	1391.4	1214.0	20.7	212.1	1335.8	219.5	1024.4				

TABLE 8 (SI). MECHANICAL PROPERTIES OF INCONEL 718 SOLUTION TREATED AND AGED SHEET (Continued)

Thickness, mm	Grain Direction	Specimen No.	Tensile				Compressive		Ultimate Shear Strength, MPa	Bearing			
										e/D = 1.5		e/D = 2.0(1)	
			Ultimate Strength, MPa	Yield Strength, MPa	Elongation, Percent	Modulus, GPa	Yield Strength, MPa	Modulus, GPa		Ultimate Strength, MPa	Yield Strength, MPa	Ultimate Strength, MPa	Yield Strength, MPa
2.0	L	1	1383.1	1187.3	21.5	205.5	1264.5	213.0	1057.0	2141.6	1580.3	3046.2	1998.9
		2	1382.4	1185.9	21.0	204.1	1266.6	211.0	1037.0	2325.7	1738.9	3031.0	1985.8
		3	1361.8	1185.9	21.5	206.2	1261.8	213.0	1007.4	2290.5	1764.4	3061.4	1960.2
		Avg.	1375.8	1186.4	21.3	205.3	1264.3	212.3	1033.8	2252.6	1694.5	3046.2	1981.6
	LT	1	1363.1	1179.7	21.0	212.4	1274.2	211.0	1040.4	2270.5	1718.9	3006.9	1963.7
		2	1361.1	1185.2	21.5	213.0	1274.2	215.8	975.0	2300.9	1714.8	3020.7	1958.9
		3	1388.0	1188.0	20.0	205.5	1272.8	215.1	1034.9	2300.9	1684.4	3037.9	1996.1
		Avg.	1370.7	1184.3	20.8	210.3	1273.7	214.0	1016.8	2290.8	1706.0	3021.8	1972.9
2.8	L	1	1460.4	1263.8	18.5	204.1	1356.9	208.9	970.8	2341.5	1734.1	3087.6	2146.4
		2	1457.6	1266.6	-	205.5	1341.1	204.1	912.2	2382.9	1768.6	3007.6	2145.0
		3	1457.6	1262.5	19.0	208.2	1358.0	220.6	947.4	2296.0	1834.8	2997.9	2105.0
		Avg.	1458.5	1264.3	18.8	205.9	1348.7	211.2	943.5	2340.1	1779.2	3031.0	2132.1
	LT	1	1439.0	1272.1	18.0	211.7	1365.9	221.3	987.4	2323.6	1827.9	3060.7	2113.3
		2	1437.6	1268.0	19.0	211.0	1365.9	235.8	994.2	2329.8	1798.2	2964.2	2014.7
		3	1439.7	1269.4	18.0	213.0	1366.6	225.5	999.8	2318.1	1816.1	2953.8	2034.7
		Avg.	1438.8	1269.8	18.3	211.9	1366.1	227.5	993.8	2323.8	1814.1	2992.9	2054.2
3.2	L	1	1403.1	1209.4	21.0	200.6	1313.5	218.6	939.8	2316.7	1759.6	3033.1	2052.6
		2	1399.0	1205.9	21.0	205.5	(4)	(4)	941.8	2240.9	1780.3	3023.4	2007.8
		3	1399.7	1203.9	20.5	202.7	1329.4	220.6	961.8	2314.0	1819.6	2975.9	2060.2
		Avg.	1400.6	1206.4	20.8	202.9	1321.4	219.6	947.8	2290.5	1786.5	3010.8	2040.2
	LT	1	1386.6	1203.9	20.5	209.6	1323.8	220.0	978.4	2266.4	1854.1	3034.5	2044.4
		2	1385.9	1205.9	20.0	207.5	1319.0	218.6	946.0	2294.7	1750.0	3015.2	2062.3
		3	1387.3	1211.4	20.0	208.2	1323.2	215.1	1010.8	2305.0	1713.4	3031.0	2065.0
		Avg.	1386.6	1207.1	20.2	208.4	1322.0	217.9	978.4	2288.7	1772.5	3026.9	2057.2

TABLE 8(SI). MECHANICAL PROPERTIES OF INCONEL 718 SOLUTION TREATED AND AGED SHEET (Concluded)

Thickness, mm	Grain Direction	Speci-men No.	Tensile				Compressive		Ultimate Shear Strength, MPa	Bearing			
										e/D = 1.5		e/D = 2.0(1)	
			Ultimate Strength, MPa	Yield Strength, MPa	Elong-ation, Percent	Modulus, GPa	Yield Strength, MPa	Modulus, GPa		Ultimate Strength, MPa	Yield Strength, MPa	Ultimate Strength, MPa	Yield Strength, MPa
4.7	L	1	1390.7	1189.4	20.0	199.3	1270.0	209.6	981.8	2293.3	1752.0	2886.2	2019.5
		2	1389.3	1183.9	22.0	199.3	1270.0	211.7	996.3	2317.4	1716.8	2964.2	2038.8
		3	1388.6	1187.3	20.0	201.3	1270.7	208.2	1012.2	2278.1	1716.8	2977.3	2029.9
		Avg.	1389.5	1186.9	20.7	200.0	1270.2	209.8	996.8	2296.3	1728.5	2942.6	2029.9
	LT	1	1386.6	1198.4	20.5	204.1	1292.8	216.5	980.2	2320.2	1756.2	2930.4	2049.9
		2	1384.5	1198.4	20.5	204.8	1298.3	224.8	1029.4	2203.6	1800.3	2949.7	2056.8
		3	1385.2	1201.1	21.0	200.6	1297.6	216.5	1018.4	2181.6	1751.3	3003.5	2075.4
		Avg.	1385.4	1199.3	20.7	203.2	1296.2	219.3	1009.4	2235.1	1769.3	2961.2	2060.7
6.4	L	1	1374.9	1189.4	21.0	197.2	1261.8	215.8	1026.7	2302.2	1777.5	2811.1	1889.2
		2	1365.2	1181.8	21.5	200.0	1262.5	217.9	1052.2	2284.3	1734.1	3004.8	2047.8
		3	1366.6	1176.3	22.0	197.2	1263.8	216.5	1021.8	2306.4	1749.3	3027.6	2027.1
		Avg.	1368.9	1182.5	21.5	198.1	1262.7	216.7	1033.6	2297.6	1753.6	2947.8	1988.0
	LT	1	1371.4	1210.1	20.0	211.0	1295.6	219.3	1028.0	2300.9	1775.5	2999.3	2023.7
		2	1376.9	1205.2	19.5	202.0	1295.6	224.8	1037.0	2324.3	1794.1	3043.4	2133.3
		3	1373.5	1209.4	20.0	205.5	1293.5	220.0	1046.7	2302.9	1775.5	3016.6	2223.6
		Avg.	1373.9	1208.2	19.8	206.2	1294.9	221.4	1037.2	2309.4	1781.7	3019.8	2126.9

(1) Specimen numbers for e/D = 2.0 were 4 through 6.
(2) Specimen buckled before yield strength.
(3) Specimen failed in surface flaw--not included in average.
(4) Load deflection curve erratic.
(5) Excessive bending of specimen.

curves for each grain direction are presented in Figure 32. The tensile stress-strain curves were constructed in the same manner as those for 7149-T73 hand forgings.

Compression. The results of compression tests are shown in Tables 8 and 8(SI). The compression specimens from the 0.016-inch sheet buckled before the yield strength was achieved. Thin compression specimens with high yield strengths are prone to buckling during testing. Compressive modulus of elasticity values are listed in Tables 8 and 8(SI) in addition to compressive yield strengths. Typical compressive stress-strain curves are presented in Figure 33 for each grain direction. The compressive stress-strain curves were constructed in the same manner as those for 7149-T73 hand forgings.

Shear. The results of tension-shear tests are shown in Tables 8 and 8(SI). The 0.016-inch-thick sheets were not tested to determine shear strength due to the anticipated instability of thin tension-shear specimens during testing.

Bearing. The results of the bearing tests are shown in Tables 8 and 8(SI). The 0.016-inch-thick sheet was not tested to determine bearing strengths due to the anticipated instability of thin bearing specimens during testing. The bearing specimens from the 0.045- and 0.050-inch-thick sheets exhibited bending and instability during testing thereby invalidating the test results.

Fatigue. The results of the axial-stress fatigue tests are presented in Tables 9 and 10. All fatigue test specimens were taken from the 0.109-inch-thick sheet. Fatigue tests were conducted only in the long transverse grain direction utilizing unnotched and notched, $K_t = 3$, specimens. Tests were conducted at three stress ratios, $R = -0.5$, $R = 0.1$, and $R = 0.5$. The fatigue data were analyzed in accordance with Section 9.3.4 of MIL-HDBK-5 and S/N curves in Figures 34 and 35 constructed accordingly.

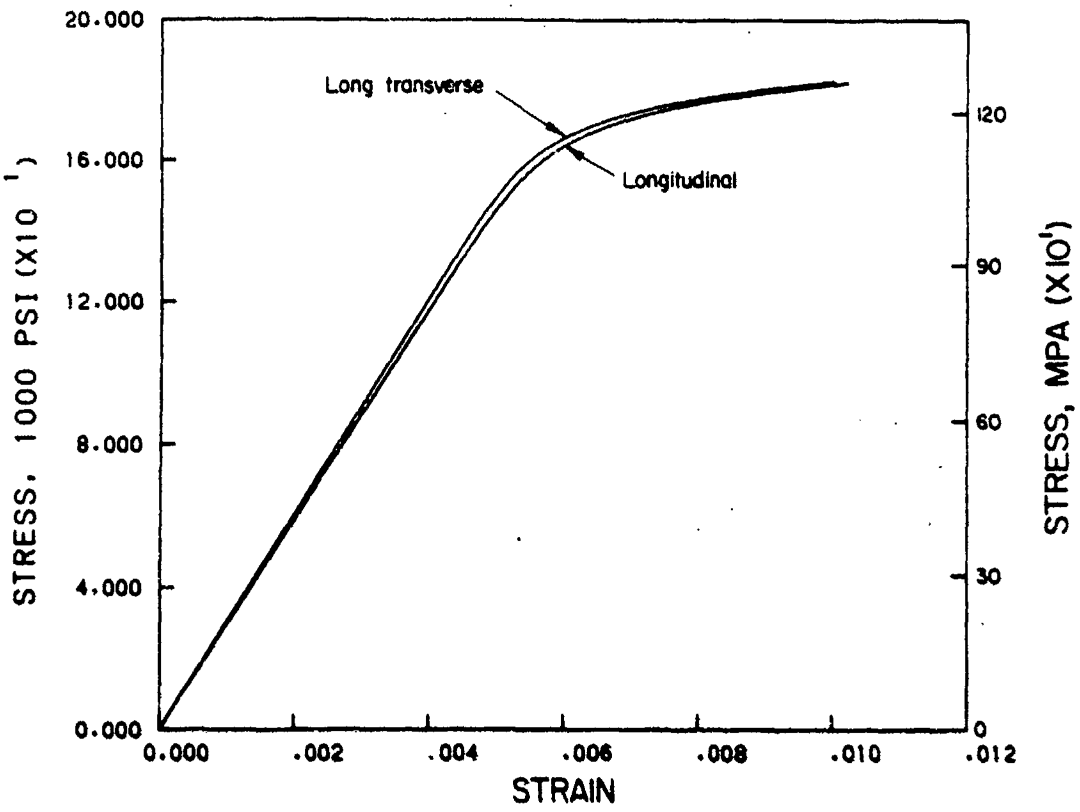


Figure 32. Typical tensile stress-strain curves for Inconel 718 solution treated and aged sheet.

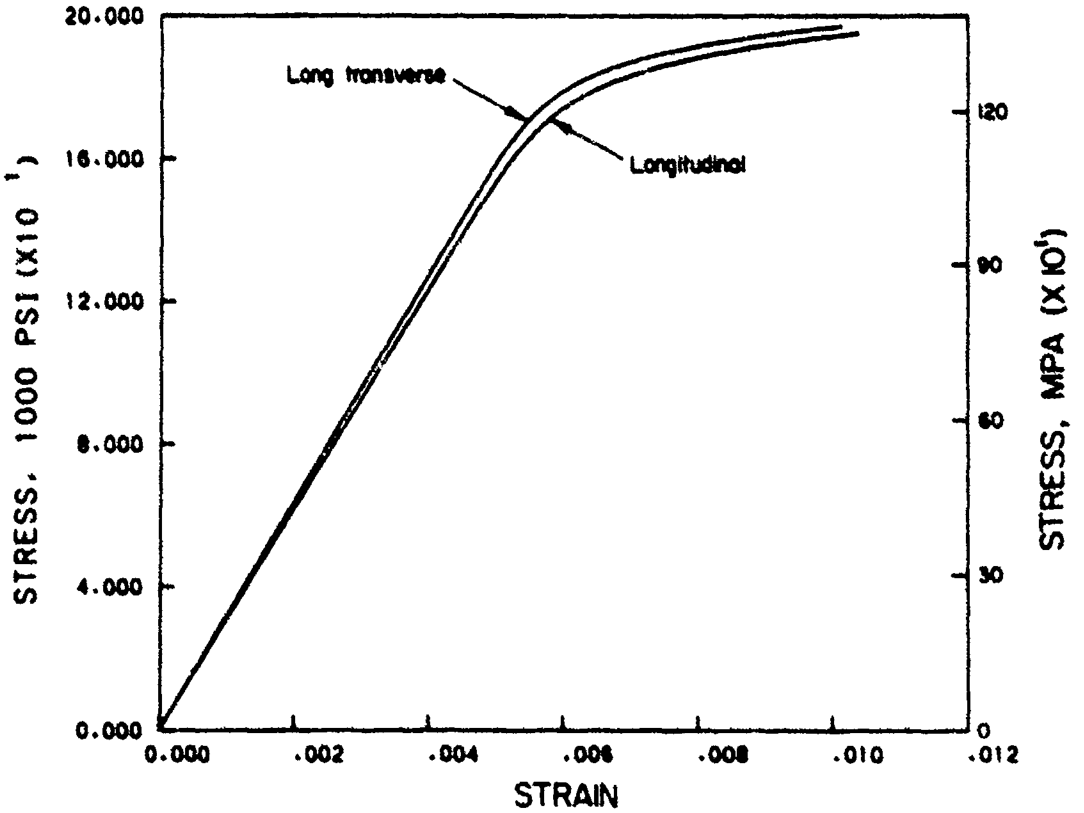


Figure 33. Typical compressive stress-strain curves for Inconel 718 solution treated and aged sheet.

TABLE 9. UNNOTCHED FATIGUE DATA FOR INCONEL 718 SOLUTION TREATED AND AGED SHEET--LONG TRANSVERSE DIRECTION.

Specimen ID	Maximum Stress ksi (MPa)	R-ratio	Cycles to Failure
EFT33	170.0 (1172.2)	-0.5	9,240
EFT35	170.0 (1172.2)	-0.5	10,099
EFT31	160.0 (1103.2)	-0.5	15,388
EFT29	120.0 (827.4)	-0.5	53,791
EFT37	120.0 (827.4)	-0.5	59,951
EFT23	80.0 (551.6)	-0.5	322,072
EFT21	80.0 (551.6)	-0.5	344,199
EFT39	70.0 (482.7)	-0.5	539,799
EFT27	70.0 (482.7)	-0.5	616,000
EFT25	50.0 (344.8)	-0.5	DNF (1)
EFT5	170.0 (1172.2)	+0.1	38,225
EFT3	130.0 (896.4)	+0.1	71,348
EFT11	130.0 (896.4)	+0.1	93,617
EFT9	100.0 (689.5)	+0.1	269,042
EFT1	100.0 (689.5)	+0.1	284,034
EFT13	80.0 (551.6)	+0.1	1,047,562
EFT7	80.0 (551.6)	+0.1	1,368,427
EFT15	70.0 (482.7)	+0.1	- (2)
EFT17	65.0 (448.2)	+0.1	DNF
EFT19	65.0 (448.2)	+0.1	DNF
EFT51	175.0 (1206.6)	+0.5	86,795
EFT43	170.0 (1172.2)	+0.5	136,036
EFT41	160.0 (1103.2)	+0.5	168,986
EFT45	140.0 (965.3)	+0.5	263,693
EFT53	140.0 (965.3)	+0.5	270,866
EFT47	120.0 (827.4)	+0.5	546,852
EFT55	120.0 (827.4)	+0.5	610,687
EFT57	110.0 (758.5)	+0.5	734,315
EFT59	100.0 (689.5)	+0.5	976,490
EFT49	100.0 (689.5)	+0.5	DNF

(1) DNF--did not fail; test ran to 10,000,000 cycles and stopped.

(2) Failed in grips.

TABLE 10. NOTCHED, K_t = 3, FATIGUE DATA FOR INCONEL 718 SOLUTION TREATED AND AGED SHEET--LONG TRANSVERSE DIRECTION.

Specimen ID	Maximum Stress ksi (MPa)	R-ratio	Cycles to Failure
EFT46	100.0 (689.5)	-0.5	4,950
EFT54	100.0 (689.5)	-0.5	4,990
EFT44	80.0 (551.6)	-0.5	10,310
EFT56	60.0 (413.7)	-0.5	34,610
EFT22	60.0 (413.7)	-0.5	35,400
EFT48	50.0 (344.8)	-0.5	76,820
EFT50	40.0 (275.8)	-0.5	244,310
EFT52	30.0 (206.9)	-0.5	76,680
EFT58	30.0 (206.9)	-0.5	5,120,720
EFT60	25.0 (172.4)	-0.5	DNF (1)
EFT20	120.0 (827.4)	+0.1	7,630
EFT6A	100.0 (689.5)	+0.1	12,920 (2)
EFT14	90.0 (620.6)	+0.1	21,660
EFT2	80.0 (551.6)	+0.1	24,920
EFT18	65.0 (448.2)	+0.1	53,100
EFT4	50.0 (344.8)	+0.1	58,130
EFT16	50.0 (344.8)	+0.1	309,560
EFT8	45.0 (310.3)	+0.1	251,290
EFT12	45.0 (310.3)	+0.1	277,210
EFT10	40.0 (275.8)	+0.1	DNF
EFT6	30.0 (206.9)	+0.1	DNF
EFT38	160.0 (1103.2)	+0.5	12,820
EFT36	150.0 (1034.3)	+0.5	15,520
EFT34	140.0 (965.3)	+0.5	19,800
EFT32	120.0 (827.4)	+0.5	34,230
EFT30	100.0 (689.5)	+0.5	60,610
EFT28	80.0 (551.6)	+0.5	85,210
EFT42	80.0 (551.6)	+0.5	135,380
EFT26	70.0 (482.7)	+0.5	318,980
EFT24	60.0 (413.7)	+0.5	DNF
EFT40	60.0 (413.7)	+0.5	DNF

(1) DNF--did not fail; test ran to 10,000,000 cycles and stopped.

(2) EFT6 and EFT6A are the same specimen. After testing at 30 ksi, EFT6 was then retested at 100 ksi.

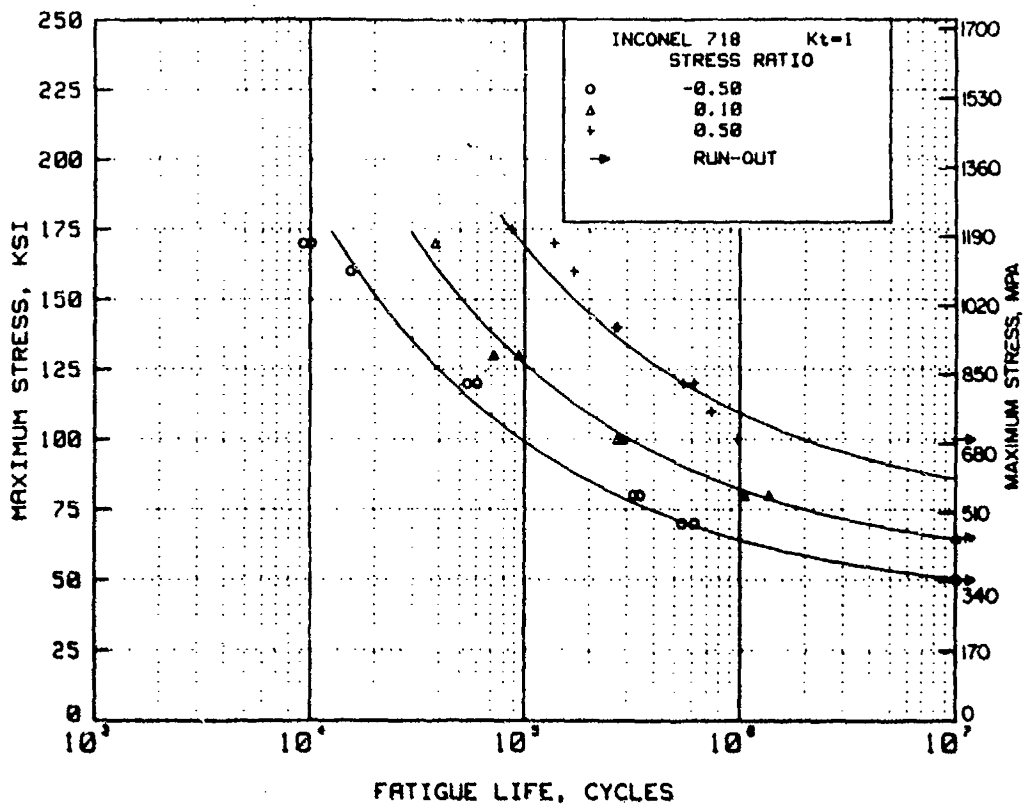


Figure 34. Unnotched axial-stress S/N curves for 0.109 inch thick Inconel 718 solution treated and aged sheet--long transverse direction.

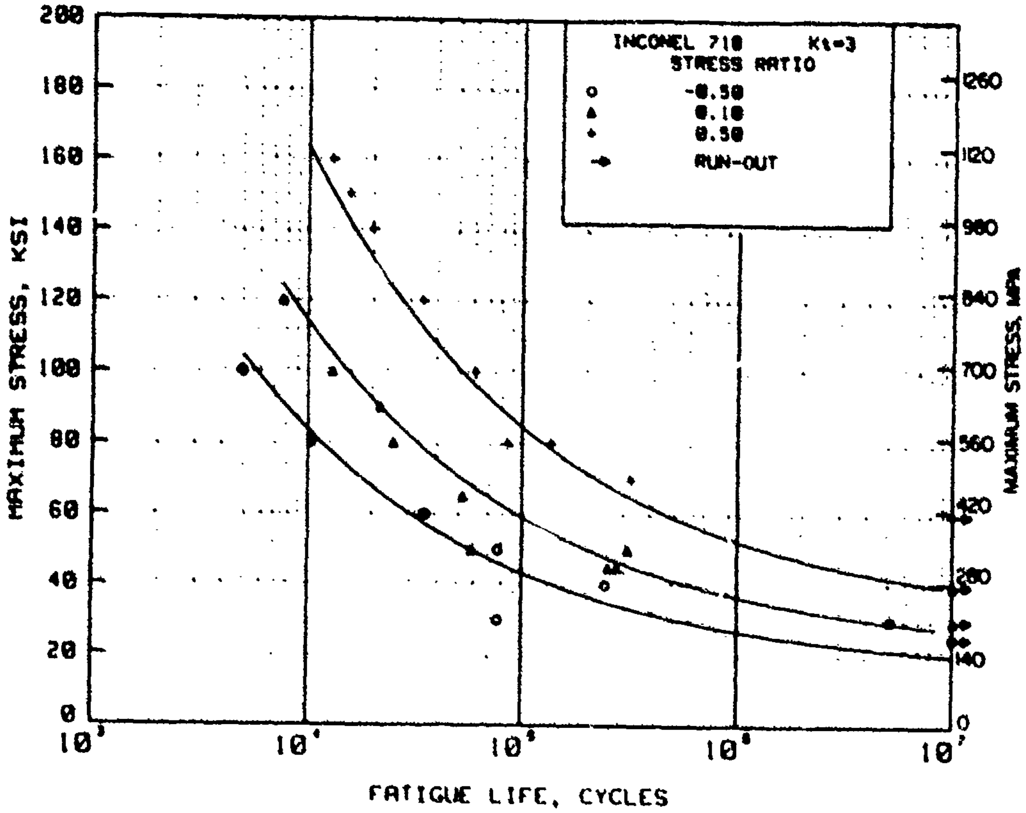


Figure 35. Notched axial-stress S/N curves for 0.109 inch thick Inconel 718 solution treated and aged sheet--long transverse direction.

APPENDIX A

TESTING PROCEDURES

APPENDIX A

TESTING PROCEDURES

Tension Tests. Tension tests were performed at room temperature in accordance with ASTM E8. Flat specimens were utilized for sheet while round specimens were employed for castings and hand forgings. Subsize round specimens were used as necessary when the size of the product would not accommodate full-size specimens. The strain rate was 0.005 inch-per-inch-per-minute, as indicated by a strain pacer, until yield strength is exceeded, after which the rate was increased to 0.1 inch-per-inch-per-minute until failure. The tensile yield strength at 0.2 percent offset, tensile ultimate strength, elongation, and the tensile modulus of elasticity were obtained from this test.

Compression Tests. Compression tests were performed at room temperature in accordance with ASTM E9. Cylindrical specimens were used for castings and hand forgings. The ends of the cylindrical specimens were parallel to 0.0002 inch and fixturing was used to maintain alignment during testing. For sheet, flat specimens were utilized and tested in a North American-type compression fixture. This fixture will accommodate sheet specimens 1 by 3 inches and up to about 1/4-inch-thick. The ends of the specimens were parallel to within 0.0002 inch. An extensometer, similar to the extension type, was fastened to the specimen at very small notches spanning a 2-inch gage length. The strain signal was generated by a linear differential transformer which was part of the extensometer with readout on an autographic recorder. For all tests the strain rate was 0.005 inch-per-inch-per-minute until yield strength was exceeded. The compressive yield strength at 0.2 percent offset and the compressive modulus of elasticity were obtained from this test.

Shear Tests. Shear tests were conducted at room temperature. For sheet material, the tensile shear specimen, as specified in Standard Test Procedure ARTC-13-S-1, was used. For 15-5PH (H935) castings, a 0.250-inch-diameter, double-shear specimen was used. For 7149-T73 hand forgings, shear-pin-type specimens were tested in an "Amsler" shear tool which minimizes bending of the shear specimen. The shear strength of aluminum alloys may vary with grain

direction. Consequently, the identity of the grain orientation of shear specimens was maintained and the shear specimens were positioned in the shear fixture so that the loading direction was according to MIL-HDBK-5 Section 3.1.2.1.1. A rivet-shear type fixture was used to test shear specimens from 15-5PH (H935) castings. The ultimate shear strength at room temperature was measured.

Bearing Tests. Bearing tests were conducted at room temperature in accordance with ASTM E238. Bearing specimens were full thickness except for products over 0.100-inch thickness, for which the bearing specimens were machined to 0.100-inch thickness. All tests were "clean pin" tests as defined in the above specification. The ultimate bearing strength and bearing yield strength at e/D ratios of 1.5 and 2.0 were measured. (The ratio of the distance between the centerline of the test hole in the bearing specimen and the edge of the specimen (e) to the diameter of the bearing hole (D) defines e/D.)

Fatigue Tests. Fatigue tests were conducted at room temperature in accordance with ASTM E466. Axial-stress tests were performed on unnotched and notched specimens to define an S/N curve between 10^3 and 10^7 cycles. Tests were conducted in the long transverse direction for sheet and hand forgings. Tests were conducted on smooth, $K_t = 1$, and notched, $K_t = 3$, specimens at three stress ratios.

APPENDIX B

SPECIMEN CONFIGURATIONS

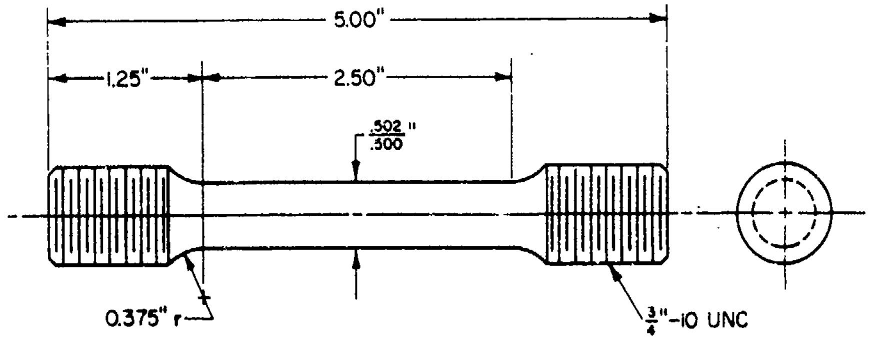


Figure B-1. Tensile specimen for 7149-T73 hand forgings.

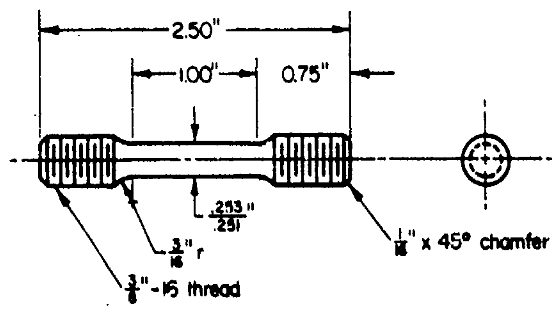


Figure B-2. Subsize tensile specimen (short transverse) for 7149-T73 hand forging.

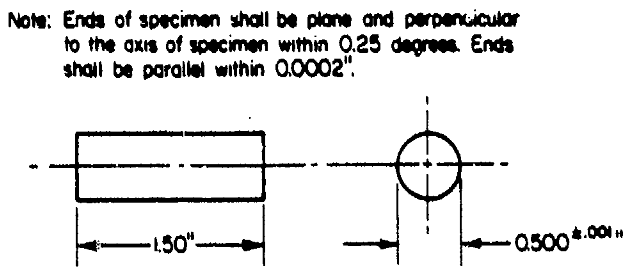


Figure B-3. Compression specimen for 7149-T73 hand forging.

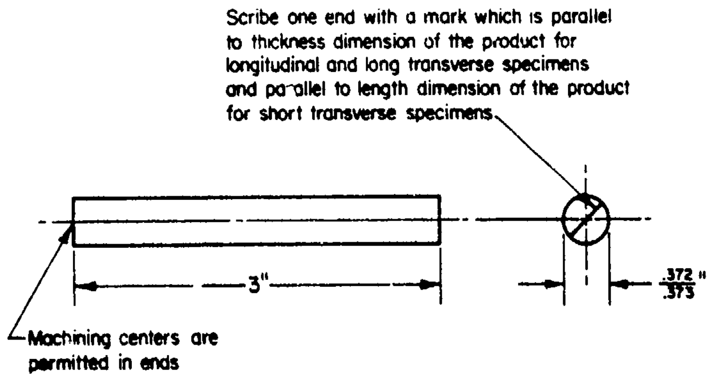
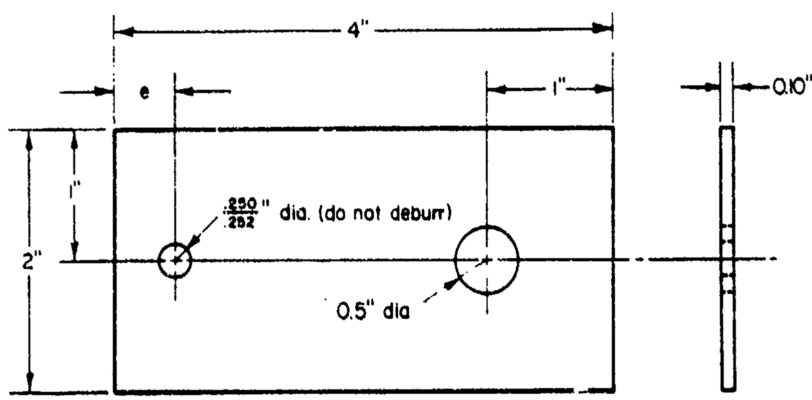


Figure B-4. "Amsler" shear specimen for 7149-T73 hand forging.



e/D	e
1.5	0.375"
2.0	0.500"

Figure B-5. Bearing specimen for 7149-T73 hand forging.

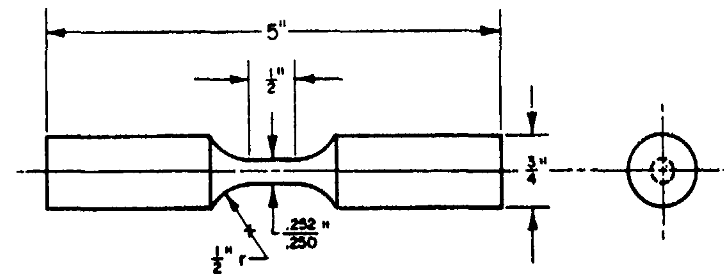


Figure B-6. Unnotched fatigue specimen for 7149-T73 hand forging.

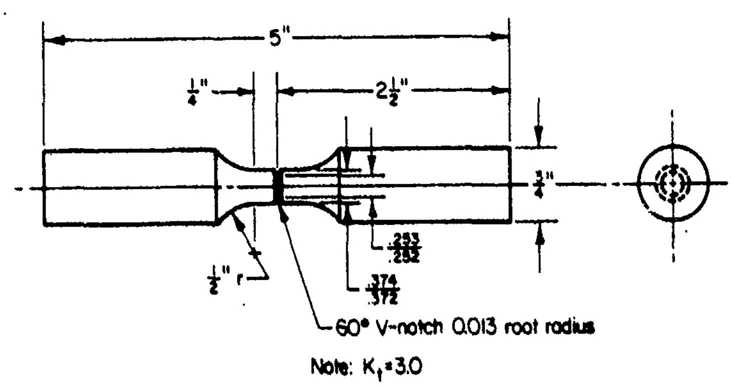


Figure B-7. Notched, $K_t = 3$, fatigue specimen for 7149-T73 hand forging.

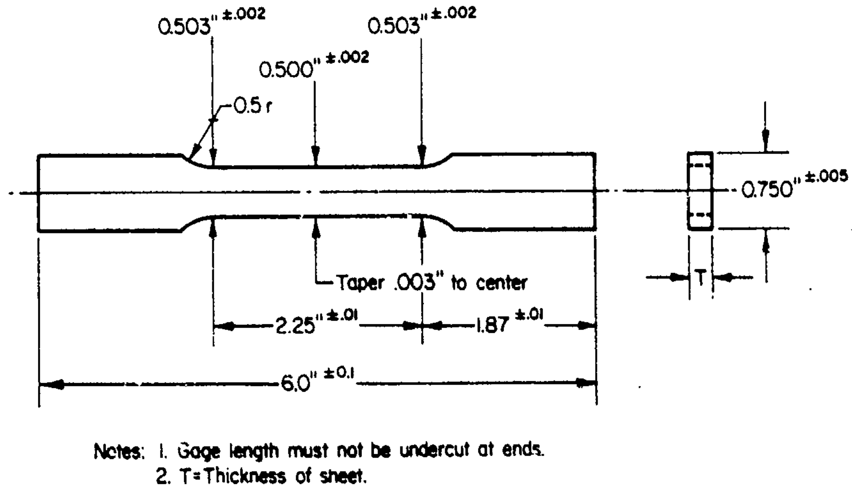


Figure B-8. Tensile specimen for Ti-15V-3Cr-3Sn-3Al sheet.

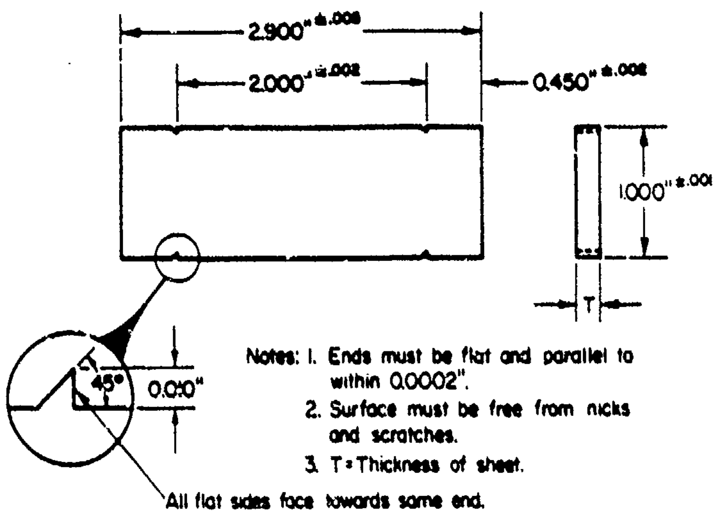


Figure B-9. Compression specimen for Ti-15V-3Cr-3Sn-3Al sheet.

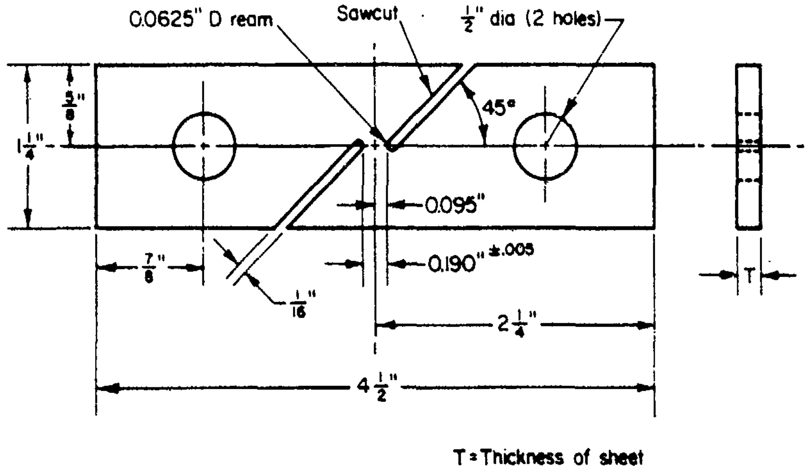
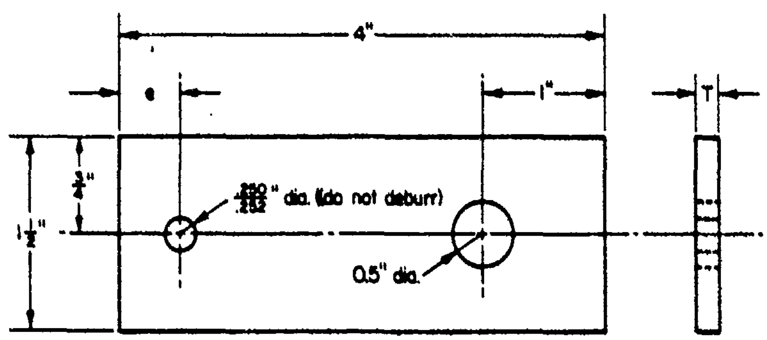


Figure B-10. Tension-shear specimen for Ti-15V-3Cr-3Sn-3Al sheet.



e/D	e
1.5	0.375"
2.0	0.500"

Figure B-11. Bearing specimen for Ti-15V-3Cr-3Sn-3Al sheet.

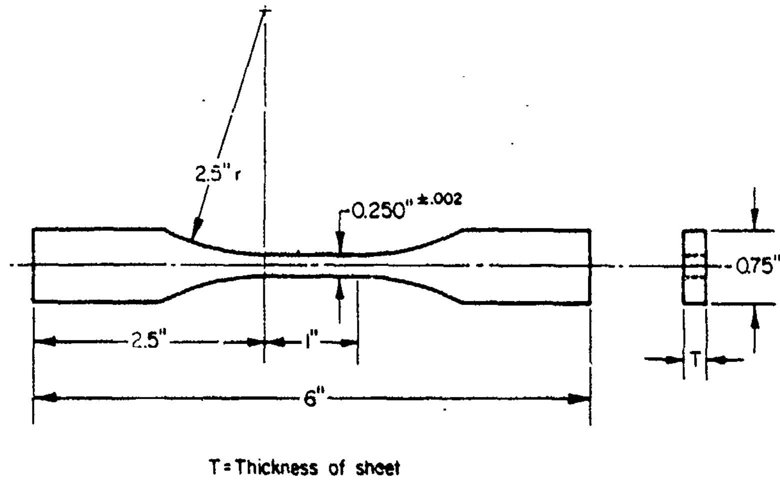


Figure B-12. Modified unnotched fatigue specimen for Ti-15V-3Cr-3Sn-3Al sheet.

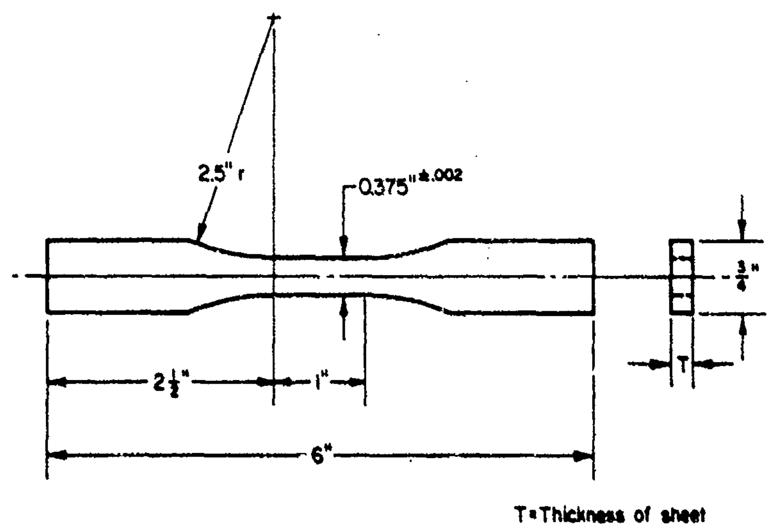


Figure B-13. Unnotched fatigue specimen for Ti-15V-3Cr-3Sn-3Al sheet.

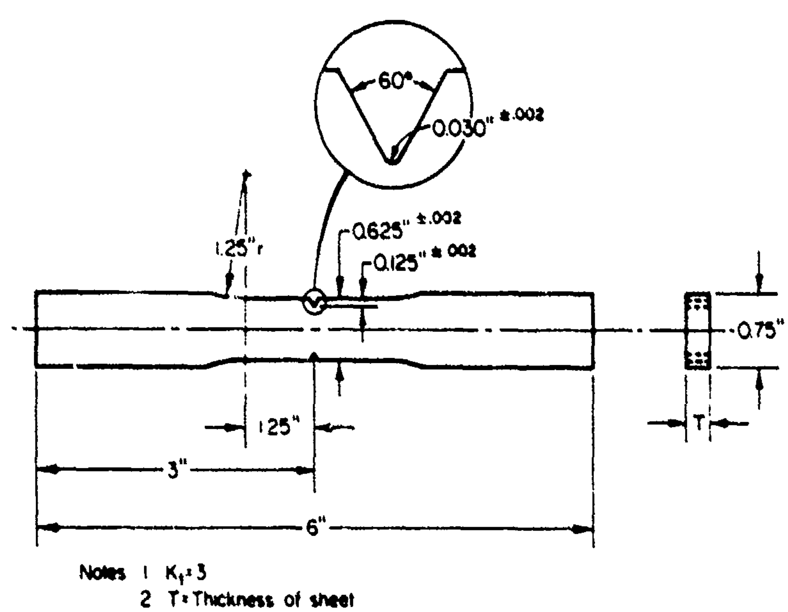


Figure B-14. Notched, $K_t = 3$, fatigue specimen for Ti-15V-3Cr-3Sn-3Al sheet.

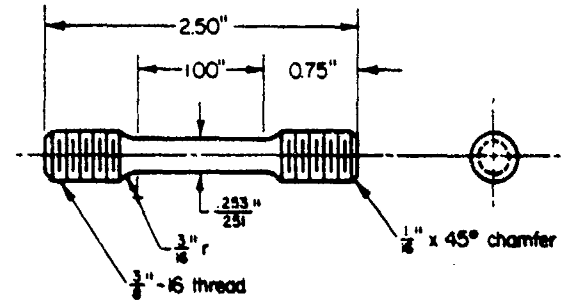


Figure B-15. Subsize tensile specimen for 15-5PH (H935) casting.

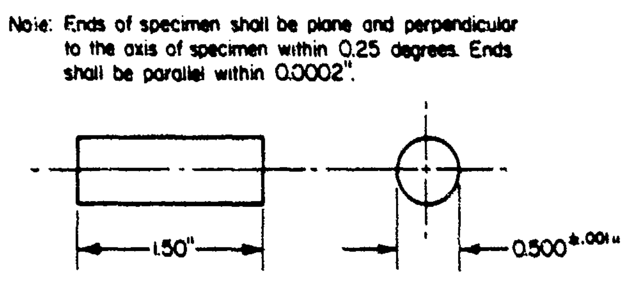


Figure B-16. Compression specimen for 15-5PH (H935) casting.

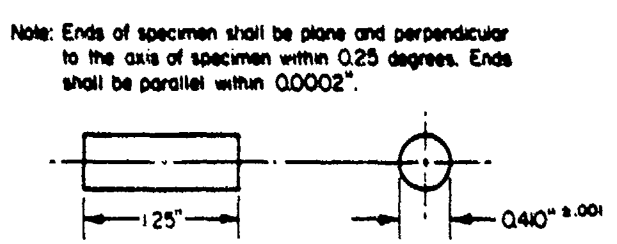


Figure B-17. Subsize compression specimen for 15-5PH (H935) casting.

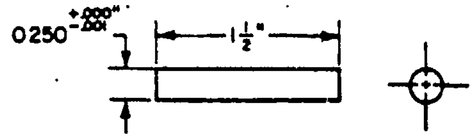


Figure B-18. Shear specimen for 15-5PH (H935) casting.

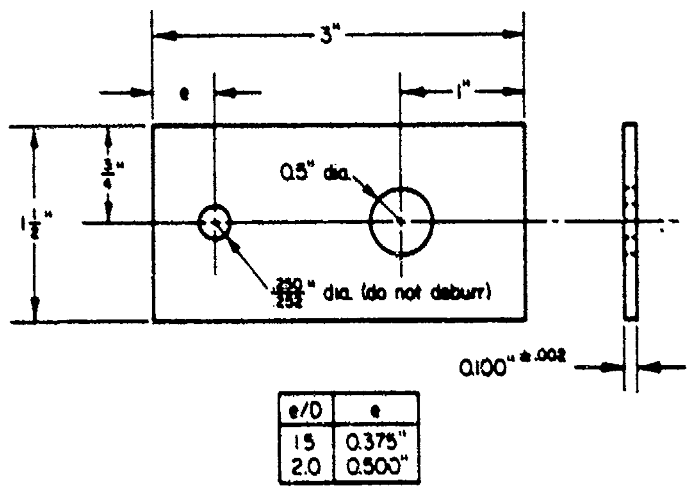


Figure B-19. Subsize bearing specimen for 15-5PH (H935) casting.

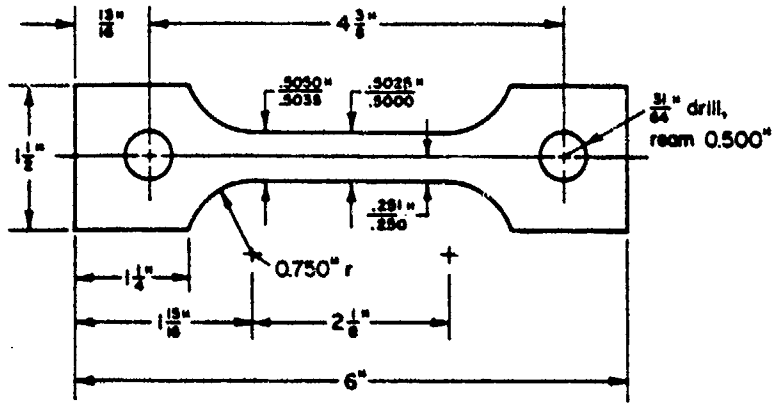


Figure B-20. Tensile specimen for Inconel 718 sheet.

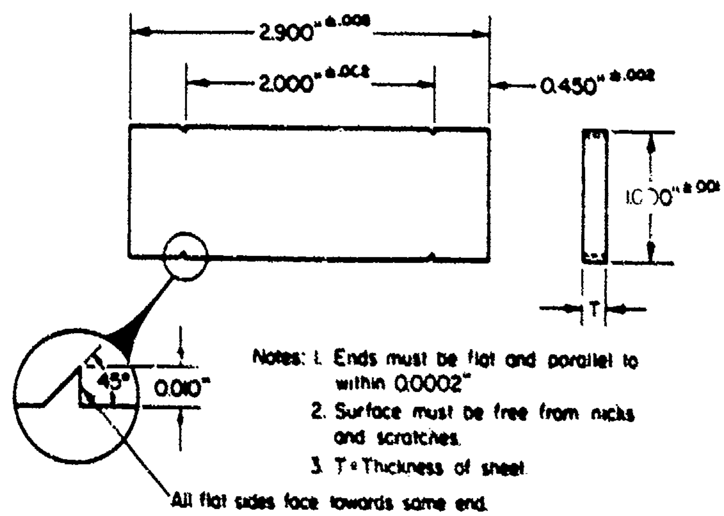


Figure B-21. Compression specimen for Inconel 718 sheet.

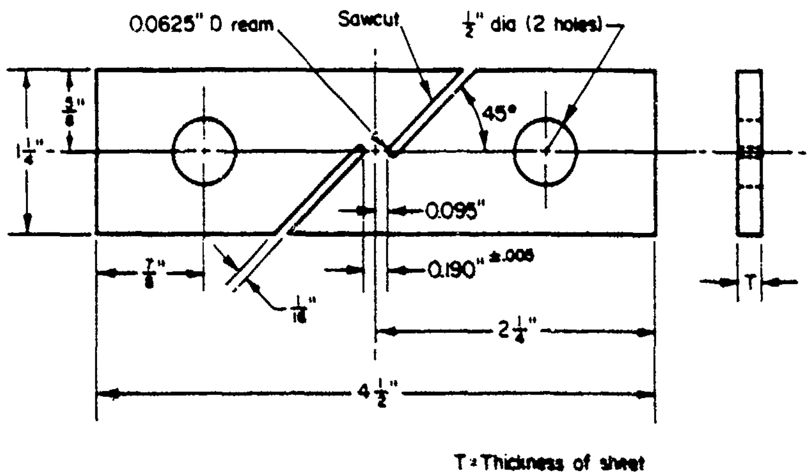


Figure B-22. Tension-shear specimen for Inconel 718 sheet.

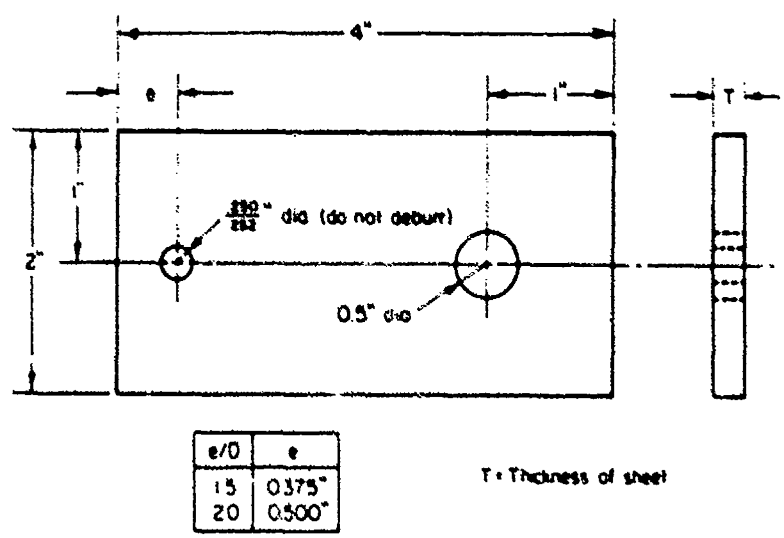


Figure B-23. Bearing specimen for Inconel 718 sheet.

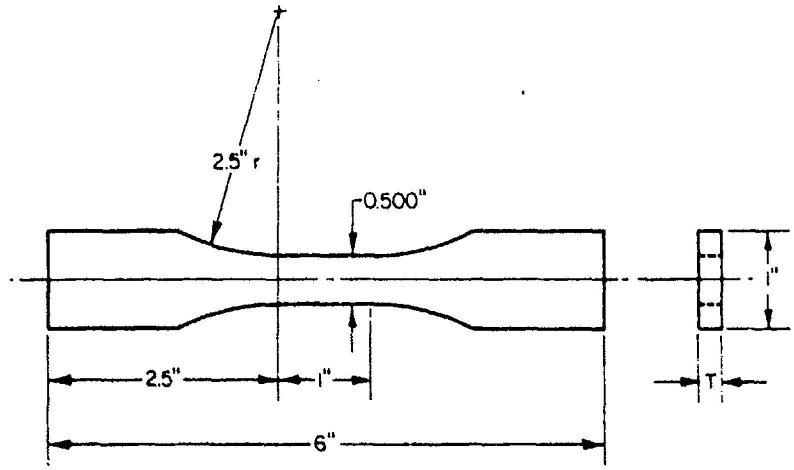


Figure B-24. Unnotched fatigue specimen for Inconel 718 sheet.

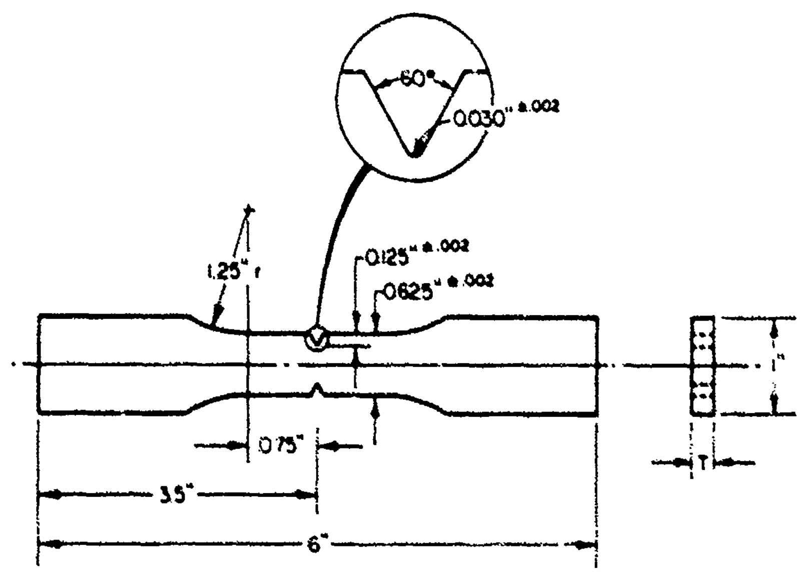


Figure B-25. Notched, K_t = 3, fatigue specimen for Inconel 718 sheet.

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END